The application of biogas technology in South Africa for small-scale energy production

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Spreuke van Salomo, hoofstuk 31.

Abstract

This study has aimed to contribute to the development of low-cost or "simple" biogas technology, i.e. the design, construction, operation and utilisation of relatively simple biogas systems in South Africa, and to explore the utilisation of the technology by lower-income groups in the rural areas of the country, particularly in the former homelands. Specific objectives included the development of biogas plants suitable for application in South Africa, and the assessment of the acceptability of the technology among potential users. Five biogas plants were constructed during the study, which provided the opportunity to test various designs and obtain response from some of the potential users of the technology.

Executive Summary

Introduction

Various efforts have been made in the past to assess the feasibility of the application of biogas technology in South Africa, mainly by reviewing the available literature. The biogas plants that existed in South Africa prior to this study had mainly been built by individuals on a one-off basis. The general aim of this study has been to contribute to the development of low-cost or "simple" biogas technology in South Africa, and to explore the utilisation of the technology by lower-income groups in the rural areas of the country, e.g. in the former homelands. Specific objectives included the development of biogas plants suitable for application in South Africa, and the assessment of the acceptability of the technology among potential users. The study was centred around the construction of five biogas plants, while an extensive literature survey was also conducted.

Potential users of biogas technology in South Africa

Three groups of potential users of biogas technology in South Africa have been considered, including smallholders and farmers who may utilise the technology for energy production on a small scale, institutions such as schools in rural areas which may utilise the technology as a sanitation option and for energy production, and large-scale intensive farming enterprises which may acquire the technology for purposes of waste stabilisation as well as energy production on a relatively large scale. This study has focused particularly on the possible utilisation of the technology by smallholders in the former homelands. This group has been defined broadly to include small farmers who may be established as part of future land reform and agricultural development programmes.

Operational aspects of biogas technology

The most important function of biogas plants which has been considered here, is the production of biogas for energy purposes. The gas production achieved in a biogas plant depends on the characteristics of the substrate as well as various operational parameters.

The concentration of the slurry in simple biogas plants which are operated on a continuous basis, should generally be between 6 % and 13 % total solids, depending on the type of substrate used. Substrates with a low carbon to nitrogen ratio, such as poultry excreta, need to be diluted more to prevent ammonia toxicity in the digester, while cattle manure can be digested successfully at a total solids concentration of 13 %.

Simple biogas plants are generally operated at ambient temperatures. As digestion becomes unsatisfactory below 20 °C, an area is generally only suitable for the implementation of simple biogas technology if the mean ambient temperature does not remain below 15 °C for a substantial length of time. Large-scale biogas plants can also be operated satisfactorily at ambient temperatures.

Similar gas yields can be achieved in digesters which are operated at different temperatures, if the retention time of the digester at the lower temperature is suitably increased. Small-scale biogas plants are generally operated at retention times of 60-80 days and even longer, for reasons such as the small quantities of substrate available.

The optimum pH for digesters is generally within the range of 6.8-7.2. A drop in pH below 6.8 is an indication of acid build-up in the slurry, which could result from sudden changes in the operating conditions, such as the temperature, or the presence of toxins in the slurry. However, toxicity is not a common problem in digesters which utilise natural substrates such as agricultural wastes. Substrates with a C/N ratio less than eight, e.g. human excreta and poultry excreta, may lead to excessive levels of ammonia in the slurry, which is toxic to the bacteria.

Design and construction of biogas plants

The advantages of the floating-drum plant are such that this design would be an attractive option in many instances. Its main drawback has been the costs associated with the maintenance and replacement of the mild steel gas drum. However, a high-density polyethylene (HDPE) gas drum may provide a suitable alternative, as it appears to satisfy most of the requirements for a gas drum such as low maintenance and a relatively long lifespan.

Based on cost considerations it would appear that the most suitable floating-drum design for digester sizes of 10 m^3 and less, would be the ferrocement digester with the HDPE gas drum. Larger plants would have to be provided with a tapered brick digester, because of the restrictions on the size of the ferrocement digester. This digester could also be built where a high water-table or a shallow rock layer prevents the excavation of a deep hole, or if the mould required for the construction of the ferrocement digester is unavailable.

A floating-drum plant fitted with an outlet pipe rather than an overflow, and an internal rather than an external guide system, is generally preferred. The water-jacket version of the tapered digester could be used for the digestion of human waste and fibrous materials, in which case an HDPE drum fitted with an external guide would have to be used.

The fixed-dome plant also has a number of important advantages. In other countries the main advantage of this design has been its low cost when constructed of bricks. However, the high level of skills required for the successful construction of a brick dome would severely limit its implementation in South Africa, as these skills are not generally available in the country. The ferrocement fixed-dome design seems to be a viable alternative to the brick design, as the risk of plant failure has been reduced considerably, and most of the skills required are available in rural areas. The costs of this plant in rural areas were found to be considerably lower than either of the floating-drum plants built during this study.

The flexible cover plant developed in this study was relatively simple to construct, and the costs of this plant were found to be significantly lower than the other plants considered here. In addition, the PVC Elvaloy used for the gas holder appears to be well-suited for this purpose. This plant therefore seems to have considerable potential for large-scale applications. However, additional research would be required to develop a large-scale plant of this design which could be implemented in South Africa.

Use of biogas as energy source

The main use of biogas which have been considered in this study, is cooking and related activities. Locally available gas burners have been adapted successfully for use with biogas, although these burners appear to be less efficient than specially made biogas burners. The biogas requirements of a farmer of family can be estimated by considering the quantities of biogas which are equivalent to current fuel consumption, or by considering the duration of use and the gas consumption rates of appliances. The biogas requirements of two families in Gazankulu for cooking and related purposes were estimated as 2 m^3 and 2.5 m^3 per day respectively, which are similar to reported figures for other areas. The estimated useful costs of biogas in rural areas, which is produced in small-scale biogas plants, appear to compare favourably with the costs of paraffin and LPG in rural areas, particularly in the case of the ferrocement fixed-dome plant.

Implementation of biogas technology on farms and smallholdings

Considerable variation is found in the quantities and properties of the manure produced by animals, which can be attributed to factors such as the breed, age and live weight of the animals as well as their diet. The quantities of manure produced by animals can be estimated on a live weight basis, as this usually provides a realistic estimate. However, not all the manure which are produced on farms and smallholdings would be available for use in a biogas plant, while the properties of the available material may differ considerably from the properties of fresh manure. On smallholdings where a limited quantity of manure would be available, it is advisable to measure the actual quantities available to ensure that the installation of a biogas plant would be feasible. The quantities and the properties of the waste that is available would depend on farming practices such as the housing of animals, and the cleaning of stables.

Based on the quantities and properties of the dung which could been collected from the cattle kraal of the Mathabela family in Gazankulu, a minimum number of 17 cattle might be required by smallholders in the former homelands in order to utilise small-scale biogas technology. This is considerably more than the required minimum number of cattle in other countries for similar conditions, i.e. the confinement of the cattle for part of the day only. This could be attributed in part to the deteriorated state of the grazing lands in parts of the former homelands, which would result in relatively low manure yields. However, it would be necessary to assess the situation in particular areas, as the grazing conditions could differ substantially.

A minimum of 50 ℓ of water would be required per day to operate a small biogas plant. However, the water required for the feeding of a digester could be reduced by 30-40 % if the liquid component of the digester effluent is used to dilute the fresh waste. The rainfall characteristics of an area can give an indication of the suitability of the area for the implementation of biogas technology, particularly in underdeveloped areas, as rainfall has an impact on the agricultural practices as well as the availability of water in an area.

Generally it would be necessary to minimise the work required to feed a biogas plant, particularly in the case of large-scale plants. This can be done by providing the cattle kraal or stable with a concrete floor, which is fitted with a collection channel directly connected to the mixing box of the biogas plant.

The most viable applications of biogas technology on small farms are found where mixed farming is practised, so that the availability of manure for the feeding of the digester is combined with a need for the digested slurry as fertiliser. In the former homelands the most feasible use for digested slurry would appear to be as fertiliser in home gardens, which can be fairly large. It would appear that parts of the Transkei, KwaZulu and Bophuthatswana have the greatest potential for the implementation of biogas technology in the former homelands, based on cattle figures in these areas.

Utilising human excreta for biogas production

A biogas plant which utilises human excreta should primarily be seen as a sanitation system with the additional benefit of gas production. The properties of human excreta, such as its low C/N ratio and the tendency of the solids to either float or settle, present some difficulties when it is utilised as a substrate in biogas plants. In addition, the wastewater from ablution blocks would generally be too dilute to provide satisfactory gas production, and would also lead to excessive sizes for biogas plants. Measures would therefore be required to reduce the quantities of water entering a digester. The relatively low volumetric gas production rates which are achieved in biogas plants utilising human excreta, compared to agricultural systems, can be attributed to a combination of these factors.

The possible health risks posed by pathogenic organisms associated with human excreta need to be considered in the design and operation of biogas systems. The most suitable plant designs for the utilisation of human excreta are the fixed-dome plant, the floating-drum plant with a water-jacket, and a digester with a separate gas holder, as all of these provide for the enclosure of the digesting material.

Two different types of biogas systems which utilise human excreta can be implemented, the first comprising a continuously operated biogas plant, i.e. digested material containing solids would leave the plant on a regular basis. The second system would be operated similarly to a septic tank, i.e. solids would be prevented from leaving the plant. The first system would require the disposal of the effluent at the institution where the biogas plant is implemented. The destruction rates of pathogens in the digester would therefore be of particular concern. Higher destruction rates are generally achieved at high temperatures or long retention times.

In simple biogas plants which are operated at ambient temperatures, retention times of 80-100 days would generally be required to ensure satisfactory destruction rates. It would probably be advisable to monitor the effluent from such plants for the presence of pathogenic organisms, in order to assess the risks posed by the effluent. The disposal and possible utilisation of the effluent would require proper management to ensure that risks are minimised. On the other hand, biogas plants operated similarly to septic tanks would not involve the handling of solids by the institution concerned, but would require desludging every few years.

Pilot plants installed during the study

The first demonstration plant was built at the homestead of the Mathabela family in Gazankulu near Acornhoek in the eastern Transvaal lowveld. A floating-drum plant comprising a ferrocement digester and a mild steel gas drum was installed. The fixed-dome plant could not be used, because of the greater risk of failure attached and the lack of the skills required for its construction. The plant was commissioned successfully, although various problems were experienced, e.g. with the digging of the hole for the digester and the initial filling of the digester.

Limited monitoring was conducted to assess the utilisation of the plant by the family. The results obtained show that the Mathabela family plant is grossly underutilised. The low feeding rate can be attributed mainly to the small quantities of dung produced by the cattle owned by the family.

The second demonstration plant was installed at the Mzimhlophe Secondary School in a peri-urban area in KwaNdebele. The biogas plant comprised a brick digester with a separate galvanised iron gas holder. This choice was determined by the fact that the digester content had to be enclosed. There was some concern about the health risks posed by the effluent, especially at a school. The plant was therefore integrated into the existing sanitation system which provided for the disposal of the effluent. The aim was to assess the risks attached to the effluent without creating a health hazard at the school. A solar-driven pump was used to pump collected solids into the digester.

After the system had been installed, problems were experienced with solid objects in the wastewater which tended to block the pump. After a brief period in operation the solar panels were stolen shortly after the security system at the school had been abolished. Various options were considered for the continuation of the project, but it was finally decided to terminate this part of the study.

The third plant was installed at the University of Pretoria's experimental farm. It was to provide an opportunity to test design aspects and to monitor operational parameters. A floating-drum plant comprising a tapered brick digester with an asbestos cement gas drum was built. After various attempts were made to seal gas leakages in the asbestos cement drum, it was finally replaced by a drum made of high density polyethylene. This proved to operate well once problems with the guiding of the drum were addressed.

The fourth plant was built at a piggery in Donkerhoek east of Pretoria. It was a pilot plant of the flexible cover design that would be suitable for large-scale applications. The digester was built of ferrocement and covered with plastic sheeting. It was successfully commissioned, but the gas holder had to be replaced after a few months due to mechanical damage. The material used for the second gas holder seems well-suited for this purpose.

The fifth pilot plant was built at a dairy south of Pretoria. It was a prototype of a ferrocement fixed-dome plant, and was completed just before the end of the study.

Utilisation of biogas technology by smallholders

The general acceptability of biogas among rural households in villages surrounding the Mathabela family plant was gauged during two surveys conducted in the area. The response to biogas has been positive in general, indicating that there are no obvious social obstacles to the implementation of the technology among rural households. However, the use of human excreta in biogas plants and the installation of multi-household plants have met with negative response.

Factors which have influenced the adoption of the technology in other countries include the effect of the technology on the work-load of households and the extent to which the technology meets perceived needs. The use of the digester effluent as fertiliser has been an important consideration in Asian countries, while the installation of units which reduce the labour required for the feeding of plants is seen as the main reason for the acceptability of the technology in Tanzania.

Interviews were conducted with members of the Mathabela family at various stages of the project to assess their experience of and response to the technology. Various problems were encountered which impacted on the effective utilisation of the plant. The most important of these were dung and water unavailability and a lack of skills and resources to maintain and manage the plant. As the family do not represent the target group of "successful farmers" in the former homelands, the ability of the more successful small holders to utilise the technology requires further investigation.

The experience with the Mathabela family plant has indicated that the successful implementation of biogas technology is dependent on a number of factors, which include technical considerations such as the availability of sufficient quantities of manure and water, as well as the skills and the resources of the users of the technology. In other countries where biogas technology has been implemented, it has been mainly the more affluent and skilled farmers who have adopted the technology. In South Africa a small percentage of smallholders in the former homelands appear to have the skills, and to some extent the resources, which should enable them to implement biogas technology successfully. This group is expected to grow in the future if a land reform programme is implemented and greater emphasis is placed on small-scale agricultural development.

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Acknowledgements

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Glossary

anaerobic bacteria	Bacteria that live and reproduce in an environment which contains no free or dissolved oxygen (Gunnerson and Stuckey 1986: 132).
anaerobic digestion	The degradation and stabilisation of organic materials brought about by the activities of anaerobic bacteria whereby biogas is produced (Gunnerson and Stuckey 1986: 132) (see Section 3.3).
carbon to nitrogen (C/N) ratio	The ratio of organic carbon content to total nitrogen content of organic materials (Gunnerson and Stuckey 1986: 133) (see Section 3.4.2).
chemical oxygen demand (COD)	A measure of the pollution potential of organic materials, which is determined by chemically oxidizing a sample (Fulford 1988: 34).
ferrocement	A building technique which comprises the plastering of cement-rich mortar onto a mesh of wire reinforcement that generally includes chicken wire (see Section 4.5).
gas yield	The volume of methane or biogas produced per kilogram of total solids or volatile solids added to the biogas plant (see Sections 3.3 and 3.5).
half-brick wall	A brick wall of which the width is equal to half the length of a standard brick.
homelands	The so-called self-governing and independent South African states that were established during the apartheid era, i.e. Transkei, Bophuthatswana, Venda, Ciskei, Gazankulu, Kangwane, KwaNdebele, KwaZulu, Lebowa and Qwaqwa.
mesophilic temperature range	Moderate temperatures (e.g. 20-40 °C) at which certain bacteria achieve optimum growth and metabolic rates (see Section 3.3.2).
methanogenic bacteria / methanogens	The group of anaerobic bacteria which utilises intermediary products formed by other bacteria to produce methane (see Section 3.3).
night soil	The mixture of faeces and urine as produced by human beings (see Section 7.2).

pathenogenic organisms / pathogens	Organisms which cause disease (see Section 7.2).
plug-flow digestion	Digestion in a plug-flow digester which occurs with very limited mixing between different sections of the slurry in the digester, as a result of its elongated shape (see Section 3.2.2).
psychrophilic temperature range	Relatively low temperatures (e.g. 10-20 °C) at which certain bacteria achieve optimum growth and metabolic rates (see Section 3.3.2).
retention time	The length of time that the substrate and bacteria theoretically remain inside the digester (see Section 3.3.3).
single-brick wall	A brick wall of which the width is equal to the length of a standard brick.
slurry	A mixture of the substrate and a liquid such as water.
substrate	Organic material, such as animal manure, plant residues and human excreta, which can be degraded by bacteria and other micro-organisms, and is utilised in biogas plants for the production of biogas (Fulford 1988: 170).
thermophilic temperature range	Relatively high temperatures (e.g. 40-65 °C) at which certain bacteria achieve optimum growth and metabolic rates (see Section 3.3.2).
total solids (TS)	A measure of the "dry" matter contained in a substrate, which is obtained by heating a sample to 105 °C (Fulford 1988: 34). It includes both suspended and dissolved substances (Gunnerson and Stuckey 1986: 135).
volatile solids (VS)	A measure of the organic matter contained in a substrate, which is volatilized and therefore lost on ignition of a sample of dry solids at 550 °C (Gunnerson and Stuckey 1986: 135).
volumetric gas production rate (VGPR)	The volume of methane or biogas produced per digester volume per day (Gunnerson and Stuckey 1986: 123) (see Section 3.3).

CHAPTER 1
INTRODUCTION

1.1 Background

Biogas technology can be defined as the means by which the anaerobic digestion of organic matter is harnessed for the production of biogas. The gas consists mainly of a mixture of methane and carbon dioxide as well as very small quantities of gases such as hydrogen sulphide and nitrogen. The implementation of the technology involves the installation and operation of a biogas plant to produce the quantities of gas required, as well as the utilisation of the gas as an energy source.

Biogas technology has been implemented all over the world. In Table 1.1 available estimates of the numbers of biogas plants which have been installed in different countries, are presented. As is evident from the table, the numbers of units which have been installed in most countries are insignificant when compared to India, and China in particular. In most cases these figures refer to small household units which produce energy mainly for domestic purposes. However, the figures for Korea and Taiwan may include some large-scale units which produce energy for agricultural purposes, while the figures pertaining to European countries and the United States of America (USA) only pertain to large-scale systems utilising agricultural substrates. There is considerable variation in the complexity and the cost of the technology which have been employed in different countries. While most of the systems in the USA and Europe involve relatively sophisticated technology (Demuynck, Nyns and Palz 1984: 52), most of the other countries have focused on the implementation of fairly simple and low-cost biogas plants.

In South Africa various efforts had been made prior to 1990 to investigate the application potential of biogas technology in South Africa, mainly by reviewing the available literature on the technology, while some consideration was given to the conditions and the needs in the rural areas. An extensive literature study was conducted by Rivett-Carnac (1982) on the implementation of biogas technology as an integrated natural resource management system. Biogas technology was also given some attention in the research studies conducted by Naeser (1983) and Williams (1988), while papers by Pretorius (1981) and Williams and Eberhard (1986) dealt with particular aspects of the technology. Generally authors have encouraged the development of biogas technology in South Africa, with its implementation on commercial farms being regarded as economically viable under certain circumstances (Rivett-Carnac 1982: 122). Reservations have generally been expressed regarding the utilisation of the technology by black households in rural areas, for reasons such as shortages of water and organic substrate, as well as concerns regarding the economic viability and the social acceptability of the technology. However, some recommendations have been made regarding the implementation of biogas technology in these areas, which included the following (Rivett-Carnac 1982: 124):

- The assessment of local attitudes towards biogas technology, as well as the assessment of current practices that would impact on the applicability of the technology.

- The development of low-cost biogas plants utilising indigenous materials and building techniques.

- The incorporation of biogas technology into integrated rural development programmes whereby its full potential could be realised.

A number of biogas plants were installed in South Africa prior to this study, mostly by individuals who had an interest in the technology. The following systems have come to the attention of the author during the course of this study:

- Two 85 m^3 digesters, among others, that were built by Mr John Fry on a pig farm near Rustenburg in the 1950's (Fry 1974).

- A number of small digesters that were built by Mr Niel Alcock at Mdukutshani farm near Tugela Ferry in the 1970's (Naeser 1983: 137).

- A 9 m^3 digester that was built by Professor Dieter Holm on a smallholding close to the Hartebeespoortdam in the 1970's (Holm, Holm and Jordaan 1986).

- A 136 m^3 digester that was built by Mr N Steyn on a farm near Barkly-East, and was in operation during the 1980's (Williams and Eberhard 1986).

- A small digester that was installed at a primary school close to Hillcrest in Natal, by Mr James Rivett-Carnac of the Institute of Natural Resources in the early 1980's[1].

- A small-scale digester that was installed at the Economic Rural Development Workshop of the Gazankulu Development Corporation in Giyani in the 1980's (Coertze 1991: 13).

All of these units had been in operation at some stage, but to the author's knowledge only the digester owned by Professor Holm has been utilised during the past few years. This plant is fed with horse manure supplemented by human excreta, and the gas is utilised for cooking purposes by the Holm family (Holm *et al* 1986). It would appear that none of the other small-scale systems listed above had been properly evaluated and documented in terms of aspects such as the cost-effectiveness of the plant design, the response of people in the area to the technology, problems which had been experienced, or the reasons for the discontinuation of the project. According to Professor Coertze of the Department of

[1]Personal communication with Mr Mark Gandar, previously of the Institute of Natural Resources.

Anthropology of the University of Pretoria[2], local people had shown considerable interest in the digester that was built in Giyani.

Table 1.1: Estimated number of biogas plants installed in different countries.

Continent	Country	Number of installed biogas plants	Date of estimate
Africa	Burundi	192	1990
	Egypt	100	1990
	Ivory Coast	50	1990
	Kenya	300	1990
	Mali	75	1990
	Morocco	250	1990
	Rwanda	< 200	1990
	Sudan	40	1990
	Tanzania	320	1990
	Tunisia	28	1990
Asia	Bangladesh	500	1990
	Bhutan	54	1990
	People's Republic of China	10 million (50 % operational)	1990
	India	1 260 000	1990
	Indonesia	200	1990
	Korea	30 000	1979
	Myanmar	< 2 000	1990
	Nepal	5 959	1990
	Philippines	800	1990
	Taiwan	1 200	1982
	Thailand	3 000	1984
America	Brazil	8 300	1990
	Caribbean Islands	190	1990
	Nicaragua	24	1990
	United States of America	< 100	1985
Europe	European Community and Switzerland	378	1982

Sources: Fulford (1988: 1); Buhl-Böhnert (1990: 3); and Demuynck *et al* (1984: 113).

[2]Personal communication.

1.2 Objectives and scope of the study

The general aim of this study has been to contribute to the development of low-cost or "simple" biogas technology, i.e. the design, construction, operation and utilisation of relatively simple biogas systems in South Africa, and to explore the utilisation of the technology by lower-income groups in the rural areas of the country, particularly in the former homelands[3]. The following objectives were identified in this regard:

- To develop low-cost biogas plants which can be built locally, particularly in the former homelands, utilising as far as possible locally available materials and skills.

- To develop practical guidelines regarding the operation of relatively simple biogas plants for the optimal production of biogas.

- To establish the requirements for the successful utilisation of biogas technology by potential users in the former homelands.

The primary focus of this study has been small-scale applications of biogas technology in the underdeveloped areas of South Africa, i.e. the former homelands, for the production of biogas as a domestic energy source. However, the following aspects of the technology have also received some attention:

- Small-scale applications in areas other than the former homelands.

- Relatively simple and low-cost large-scale biogas systems for implementation on commercial farms.

- The application of the technology for the production of energy at rural institutions such as schools, using human excreta.

- Benefits of the technology such as the stabilisation of organic waste, and the production of organic fertiliser.

The installation of five pilot-plants was central to the study. These served a number of purposes, such as the testing of various designs, the monitoring of operational parameters, the demonstration of the technology to potential users, obtaining practical experience regarding the operation of biogas plants, assessing the costs of producing biogas etc. These matters are discussed in great depth in this dissertation. In addition, an extensive literature study was conducted to collate information of relevance to the study.

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[3]The term homelands is used here to include all the so-called self-governing and independent states that were established during the apartheid era in South Africa, i.e. the Transkei, Ciskei, Venda, Bophuthatswana, Gazankulu, Kangwane, KwaNdebele, KwaZulu, Lebowa and Qwaqwa.

Most of the work conducted during this study formed part of a project that was funded by the Chief Directorate: Energy, of the Department of Mineral and Energy Affairs[4] (DMEA) for a period of three years from April 1990 to March 1993. In addition, the CSIR funded the development of a particular unit when a need for this was identified during the main project. The demonstration of the technology to potential users, particularly in the former homelands, in order to assess their response to the technology, received considerable emphasis in the DMEA-funded project. However, it has been the author's view that the development of the technology to a satisfactory level of performance should receive precedence, as the failure of a system which is installed prematurely at a "real-life" location can have a considerable impact on the attitudes of potential users to the technology. The tension between these two aspects of the work conducted during this study, will become evident in the discussion that follows.

The work was conducted by the Division of Water Technology (WATERTEK) of the CSIR, with assistance from employees of the Division of Building Technology. During the first year of the DMEA-funded project Mr Cecil Chibi served as project leader, but the author acquired this position in May 1991 after Mr Chibi had left WATERTEK. A shortage of manpower was experienced during the period involved, which affected many of the activities undertaken during this study, e.g. problems encountered with the pilot-plants often could not be addressed immediately.

1.3 Chapter outline

The dissertation starts with a discussion of the various groups of potential users of biogas technology in South Africa in Chapter 2. Operational aspects of biogas technology are considered in Chapter 3, and some low-cost biogas plant designs are discussed in Chapter 4. In Chapter 5 the application of biogas technology on farms and smallholdings is considered, with particular emphasis on practical considerations. The use of biogas as energy source is considered in Chapter 6. The utilisation of human excreta for the production of biogas technology is discussed in Chapter 7. The five pilot-plants that were installed during this study are discussed in Chapter 8, and in the final chapter the utilisation of the technology by smallholders in the former homelands is considered.

[4]The project was commissioned in 1990 by the National Energy Council (NEC) which was subsequently incorporated in the Department of Mineral and Energy Affairs.

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CHAPTER 2

POTENTIAL USERS OF BIOGAS TECHNOLOGY IN SOUTH AFRICA

2.1 Introduction

In this chapter an attempt will be made to identify some of the individuals and institutions in South Africa which could possibly utilise biogas technology. This will serve as background to the rest of this dissertation in which the utilisation of the technology by some of these groups will be considered. No attempt is made here to assess the feasibility of the implementation of the technology by the different groups, as this matter will receive some attention in subsequent chapters. In general it is expected that only a fraction of the potential users would be able to utilise the technology effectively. In India, for example, it has been estimated that biogas technology is only accessible to 5-10 % of the rural population (Kijne 1984: 60).

2.2 Farmers and smallholders

This category comprises farmers and smallholders who could implement biogas technology on a small scale to produce fuel for domestic use by the farmer and/or farmworker households, or to run engines for water pumping etc. For example, Professor Dieter Holm's biogas plant on his smallholding close to the Hartebeespoortdam is fed with horse manure supplemented by human excreta and provides gas for domestic purposes (Holm *et al* 1986).

The total number of commercial farmers in South Africa (excluding the former homelands) has been estimated as 62 000 (Bembridge 1990: 17), and indications are that a similar number of smallholdings are found in these areas[5]. Judging by the number of enquiries received from the latter during this study, this constitutes an important group of potential users of biogas technology. Gandar (1992) indicated that the number of black farmworkers who are employed on white-owned farms in South Africa is of the order of one million, while the total population involved may be more than four million people if family members are also considered.

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[5]Personal communication with Mr Raymond Auerbach of the Institute of Natural Resources in Pietermaritzburg.

According to Bembridge (1990: 21) there were approximately 3 000 commercial farmers in the former homelands (0.2 % of the rural population in these areas) who made a living from farming. In addition, he identified the following groups of smallholders in these areas:

- Progressive smallholders, including farmers on irrigation or similar projects, who adopted some recommended technologies, and who sold some produce and/or livestock, but usually did not produce adequate food for their families. This group comprised approximately 238 000 households (13 % of the rural population in the former homelands).

- Smallholders with production levels below that required for subsistence who did not usually sell any crops or livestock, comprising approximately 1 028 000 households (56 %).

The rest of the population in the rural areas of the former homelands (approximately 562 000 households or 31 % of the population) comprised resource-poor households who had no access to arable land and owned no large livestock (*ibid*).

The utilisation of biogas technology by smallholders in the former homelands received most attention during this study. These smallholders generally lack the skills and resources which have been available to white smallholders who live in the vicinity of towns and cities, and white commercial farmers in particular (Bembridge 1990: 19). Many of the findings of this investigation would be relevant to black smallholders in other parts of the country as well, e.g. smallholders who may be established as part of a future land reform programme. Indications are that the development and support of small-scale agriculture, and particularly small black farmers, will form an important part of a future agricultural policy in South Africa. A land reform programme which aims to redress the current inequalities in land ownership between black and white people in South Africa, will probably provide the basis for the development of small-scale agriculture, particularly in areas outside the former homelands. The number of black smallholders in South Africa which could possibly utilise the technology is therefore likely to increase significantly in the future.

2.3 Rural institutions

Institutions such as schools, colleges, hospitals and clinics, as well as religious and other community establishments, could possibly utilise biogas technology as a sanitation option, and to provide a source of energy for cooking, refrigeration, etc. For example, the Ananda Marga Mission, a religious establishment at Orange Farm south of Johannesburg, owns a biogas plant which had previously provided energy for cooking purposes to a creche. The plant had been operated mainly on vegetable waste, although the intension had been to utilise human excreta as well.

Only rural schools in the former homelands were considered in this study. According to De Villiers (1986: 2) these schools generally need improved sanitation facilities, as these have often been neglected in the past. Biogas could possibly be used for purposes such as cooking and heating, e.g. at secondary schools provided with homecraft centres or laboratories, and at primary schools where meals are cooked for the pupils.

An attempt was made in 1990 to obtain statistics on the schools in the former homelands by contacting all the Departments of Education involved. Only six of the departments responded to these enquiries and provided some of the information requested, which is summarised in Table 2.1. No information could be obtained on the numbers of schools provided with homecraft centres, laboratories or other cooking facilities. The percentage of schools without electricity was estimated using the information provided by the departments. It would appear that more than 90 % of schools in the former homelands, including both rural and urban schools, and primary as well as secondary schools, were without electricity at the time. This was of interest as schools with access to grid electricity could provide most of the services mentioned above by means of electricity, which would be a more attractive energy form than biogas.

Table 2.1: Schools in the former homelands without electricity (1990). The total number of schools is given in brackets where available.

Homeland	Schools without electricity		Calculated % of schools without electricity	Number of pupils in schools without electricity
	Total	Secondary		
Ciskei	627	132	-	212 695
Gazankulu	448 (496)	111 (139)	90	-
KaNgwane	about 250 (279)	(59)	90	about 56 920
KwaNdebele	212 (222)	-	95	-
Transkei	3 169 (3 261)	(246)	97	1 040 443
Venda	538	175	-	77 166

Sources: Departments of Education of the former homelands.

In addition, information on the schools in the former homelands which had been compiled in 1991, was obtained from the Research Institute for Educational Planning at the University of the Orange Free State. This information is presented in Table 2.2, together with some of the figures which had been obtained from the Departments of Education of the various homelands in 1990. A rough estimation of the percentage of schools in each of the former homelands which is located in the rural areas, is also provided.

Table 2.2: Numbers of schools and pupils in the homelands (1991). Figures obtained from the Departments of Education during 1990 are given in brackets.

Homeland	Primary schools		Secondary schools		Middle/ combined schools	Total number of schools	Estimated % of rural schools[6]
	Number	Pupils	Number	Pupils			
Gazankulu	342	247673	125 (139)	90938	27	494 (496)	80
Kangwane	223	176190	75 (59)	70626	5	303 (279)	majority
KwaNdebele	141	97043	67	52791	23	231 (222)	80
KwaZulu	2329	1205531	758	409134	28	3115	majority
Lebowa	1253	630703	615	342040	1	1869	70
Qwaqwa	87	68407	38	42530	15	140	70
Transkei	1338	988044	261 (246)	210425	1729	3328 (3261)	70
Bophutha-tswana	920	410864	158	177899	359	1437	60
Venda	466	161680	197	82349	2	665	70
Ciskei	550	192440	177	81799	2	729	50
Total	7649	4178575	2471	1560531	2191	12311	

Source: Research Institute for Educational Planning (University of the Orange Free State).

2.4 Large-scale intensive farming enterprises

Privately owned or industrial farms where large-scale intensive livestock keeping is practised, such as dairies, feedlots, chicken farms and piggeries, could possibly utilise biogas technology for the treatment of wastes, as well as the production of energy for water pumping, the heating of animal houses etc. Some degree of overlap exists between this category and the first one, as many commercial farmers are involved in large-scale intensive livestock farming. However, this category only includes large-scale applications of biogas technology, i.e. involving biogas plants larger than 50 m^3.

The following information on intensive farming enterprises has been obtained from the Meat Board, the Dairy Board, the Poultry Board and other sources:

- There are 15 registered feedlots in South Africa which handle 60 % of all the cattle slaughtered in the country (2.2 million animals per year). The number of animals at a feedlot at any time varies from 2 000 to 70 000, with an average of 20 000 - 40 000.

[6]Personal communication with Professor J Strauss of the Research Institute for Educational Planning, University of the Orange Free State.

- There are approximately 1 200 piggeries in the country, with the total number of sows ranging between 120 000 and 125 000. The number of sows owned by any one piggery ranges from 100 to 6 000, with 300 farmers owning ± 80 % of the total.

- There are approximately 9 000 dairies in the country which range in size from 20 to 2 000 cows, with an average of 80-100 cows.

- The total number of laying hens in the country at any time is of the order of 11 million. The two largest suppliers of eggs each have more than 2 million laying hens, while the number of laying hens owned by the third largest supplier is of the order of 0.6 million.

- The number of broilers that are slaughtered every week is of the order of 7 million. The three largest companies involved supply of the order of 3.5 million, 1.1 million and 0.4 million broilers per week respectively, while two other companies each supply approximately 0.2 million broilers per week. An individual farm may comprise 12 chicken houses each of which contains 30 000 broilers.

This category of potential users received little attention during this study, as the main emphasis had been on small-scale applications.

2.5 Conclusions

Three groups of potential users of biogas technology in South Africa have been considered in this chapter, including smallholders and farmers who may utilise the technology for energy production on a small scale, institutions such as schools in rural areas which may utilise the technology as a sanitation option and for energy production, and large-scale intensive farming enterprises which may acquire the technology for purposes of waste stabilisation as well as energy production on a relatively large scale.

More than 12 000 schools are found in the former homelands, most of which are located in the rural areas, and between six and seven million pupils are enrolled at these schools. The total number of commercial farmers in South Africa (excluding the former homelands) is estimated as 62 000, and indications are that a similar number of smallholdings are found in these areas. In addition, there are approximately 3 000 commercial farmers in the former homelands.

The study has focused mainly on the possible utilisation of the technology by smallholders in the former homelands, which comprise 69 % of the rural population in these areas. This group includes approximately 238 000 "progressive" smallholders, who derive some income from the sale of produce and/or livestock, but usually do not produce adequate food for their own use, as well as approximately 1 028 000 smallholders who generally do not sell any crops or livestock. In addition, small farmers who may be established as part of future land reform and agricultural development programmes, have also been considered.

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CHAPTER 3

OPERATIONAL ASPECTS OF BIOGAS TECHNOLOGY

3.1 Introduction

As mentioned in Section 1.2, this study has focused on the implementation of relatively simple biogas technology. A simple biogas plant basically comprises a tank or digester which contains the digesting material or slurry, as well as some means of collecting the gas. The digester is usually fitted with pipes through which slurry enters and leaves. Provision is made for the mixing of the slurry before it enters the digester, and for the collection and temporary storage of the digested slurry. The gas is piped directly from the biogas plant to the place where it is utilised. The digesters of simple biogas plants are usually not heated actively, but may be insulated to prevent heat-loss. However, at times the digester may be heated by means of the circulation of hot water from a solar panel, or by enclosing the biogas plant in a simple greenhouse structure as was done in Lesotho (Hutcheon 1986). Generally only very limited or no mechanical devices are employed for the mixing of the slurry inside the digester.

In this chapter the operation of simple biogas technology will be discussed. As the aim of this discussion is to provide practical guidelines for the operation of biogas plants, rather than an in-depth overview of the chemical and microbiological processes involved, some aspects will be dealt with fairly superficially. The main function of biogas plants considered in this study, has been the production of energy in the form of biogas. Particular attention will therefore be given to the effect of operational parameters and substrate characteristics on gas production. Other possible functions of biogas plants, such as the stabilisation of waste and the production of organic fertiliser, will be considered only to a limited degree.

3.2 Operating systems

Simple biogas plants can be operated in a variety of ways, which can be distinguished by the frequency and the magnitude of the feeding employed, relative to digester size.

3.2.1 Batch systems

A digester which is operated as a batch system has a limited period of operation, which may be two months or longer (Demuynck *et al* 1984: 10). It is filled with a mixture of an organic substrate and water at the onset, and no feeding of the plant takes place during the operating period. Some mixing may be employed in a batch digester (*ibid*). At the end of this period the digester is emptied completely, before the cycle is restarted. Two variations exist of the batch system, namely the fed-batch and the semi-batch systems:

A *fed-batch* (accumulation) digester is filled over a period of time by means of a small number of feedings of a substantial size (Demuynck *et al* 1984: 11). After it has been filled completely, it is operated as a batch digester. Special provision has to be made for the collection and use of the gas from the partly filled digester.

A *semi-batch* digester has a period of operation which is typically six to twelve months (Fulford 1988: 38). It is fed on a regular (e.g. daily) basis with animal manure and/or human excreta, and digested slurry leaves the digester on a regular basis. Its operation is therefore similar to that of a semi-continuous digester (see Section 3.2.2). However, some material, e.g. crop residues, remains inside the digester until it is removed at the end of its operating period. This type of digester has been utilised widely in the People's Republic of China (*ibid*).

The main disadvantages of batch digesters are the interruption in gas production when the plants are emptied, as well as the large labour input which is often required for this purpose (Demuynck *et al* 1984: 10). In addition, the gas production rate of batch and fed-batch digesters changes significantly during the period of operation. The main advantage of batch systems is the fact that any organic substrate that is suitable for biogas production can be utilised. Batch systems are particularly suitable for the digestion of fairly solid material, i.e. with a total solids content up to 30 % (see Section 3.3.1) (Fulford 1988: 35).

3.2.2 Continuous systems

A digester which is operated on a continuous basis is fed continuously or intermittently, resulting in the regular displacement of digested slurry from the plant. As a result the gas production rate remains more or less constant. In practice the plant has to be cleaned and restarted after a number of years, because of the accumulation of indigestible material, such as soil and fibrous matter, inside the digester which tend to reduce the active volume and therefore the gas production. Two different types of continuously operated simple biogas plants can be distinguished, based on the degree of mixing which occurs in the digester and the flow pattern of the slurry in the digester:

Partly mixed digesters usually have a spherical shape or an upright cylindrical shape. As a result the incoming slurry tends to mix with the slurry inside the digester. However, because of the limited degree of mechanical mixing employed in simple plants, the digester contents are never completely homogeneous (Demuynck *et al* 1984: 11). Only sophisticated plants may therefore be operated as completely mixed systems (*ibid*).

Plug-flow or horizontal displacement digesters are elongated horizontally, e.g. in the shape of a trench. Fresh slurry is added at the one end of the digester, while digested slurry leaves it at the other end. As a result very little mixing occurs between the incoming slurry and the slurry inside the digester, and each volume of slurry added to the digester tends to flow in the form of a "plug" of material through the digester. Usually the digester content is not mixed mechanically, but the flow of the slurry may be mechanically assisted (Demuynck *et al* 1984: 12).

Because of the required flow of the slurry through the digester, the concentration of the slurry in continuous systems needs to be considerably lower than in the case of batch systems, i.e. less than 15 % total solids (see Section 3.3.1). This study has mainly been concerned with biogas plants which are operated on a semi-continuous basis, i.e. where the fresh slurry is added regularly but not continuously, such as once a day.

3.3 Operating parameters

The anaerobic digestion process whereby methane is produced and the stabilisation of organic waste is achieved, derives from the complex interaction of different bacterial groups, each of which is responsible for particular stages of the process. This process is discussed in great detail by Gunnerson and Stuckey (1986: 103).

The first requirement for the successful operation of a biogas plant is for the bacterial groups to remain in dynamic but harmonious equilibrium, i.e. maintaining a stable operating environment (Gunnerson and Stuckey 1986: 8). This can be achieved under a fairly wide range of conditions, while the optimum conditions for gas production and/or waste stabilisation are often narrowly defined. The equilibrium in a digester is affected by changes in the operating parameters, which can inhibit the digestion process. In the case of a small or gradual change, the bacterial groups are often able to adapt to the changed conditions and establish a new state of equilibrium. However, if a sudden or major change occurs, digester operation can become unstable, in which case it may be necessary to intervene in the process to prevent failure (*ibid*).

The group of bacteria which is most dependent on the operating environment is the methanogens (Gunnerson and Stuckey 1986: 108) which produce methane from the intermediary products formed by other bacteria. The methanogens are fragile and slow-growing and are most sensitive to changes in the operating environment. In general it is therefore necessary to maintain the operating conditions as close as possible to the optimum for the methanogens. However, it is generally impossible to achieve the optimum operating conditions fully in simple biogas plants. Usually the aim would be to achieve the highest possible energy production within the limits of what is practically attainable.

The gas production achieved in a biogas plant can be expressed in different ways, each of which is related to a different aspect of the production process. The *volumetric gas production rate* (VGPR) is defined as the volume of methane or biogas produced per digester volume per day (Gunnerson and Stuckey 1986: 123). It is a measure of the volumetric efficiency of a digester, i.e. the degree to which the available digester volume is exploited. The VGPR of a biogas plant therefore needs to be considered when the energy cost of the biogas is determined, as an increase in the VGPR of the plant would correspond to a decrease in the cost of the biogas.

Gas production can also be expressed in relation to the mass of solid material, mostly of an organic nature, which is added to a biogas plant. The *gas yield* can be defined as the volume of methane or biogas produced per kilogram of total solids (TS) or volatile solids (VS) added to the plant (Hobson, Bousfield, Summers *et al* 1980: 245). It therefore serves as a measure of the efficiency of the digestion process or the biodegradability of the substrate or solid material (see Section 3.4.1). As the gas yield reflects the degree to which the available substrate is utilised in a plant, it is particularly important if a limited quantity of substrate is available to meet specific energy needs. In such cases it would be necessary to increase the gas yield as far as possible.

As will be discussed below, the effect of operating parameters on the volumetric gas production rate and the gas yield is not always similar, and is contradictory in some cases. For example, an increase in retention time may lead to a decrease in the VGPR and an increase in the gas yield at the same time. The operating parameters which are most suitable under particular circumstances would therefore depend on the relative importance of considerations such as energy cost, substrate availability etc.

The degree of waste stabilisation that is achieved in a biogas plant is expressed as the percentage reduction in organic matter, e.g. VS or COD (chemical oxygen demand), during the digestion process (Aubart and Fauchille 1983: 34). Generally this increases under the same conditions which provide for an increase in the gas yield.

In this section the operating parameters of greatest importance are discussed, while some of the properties of substrates which impact on gas production and digestion generally, are discussed in Section 3.4. The various operating parameters are considered separately, and when considering the effect of changes in a parameter on digestion and gas production, it is assumed that all the other parameters remain constant. However, the different parameters are inter-related, and the optimum conditions for digestion would therefore need to be defined in terms of a *combination* of all the parameters rather than the optimum values of individual parameters.

3.3.1 Slurry concentration

The slurry in a biogas plant generally comprises organic substrates in a diluted form. The slurry concentration is often expressed as the percentage of total solids (TS) or volatile solids (VS) in the slurry, i.e. the mass of TS (or VS) present in the slurry as a percentage of the mass of the slurry. It is also expressed as the mass of TS or VS present in a unit volume of slurry, or the COD (chemical oxygen demand) of the slurry (Gunnerson and Stuckey 1986: 123).

3.3.1.1 Impact on digestion and gas production

Changes in the slurry concentration affect the volumetric gas production rate (VGPR) and the gas yield in different ways, while the degree of waste stabilisation follows a pattern similar to that of the gas yield (Aubart and Fauchille 1983: 34). In some completely mixed digesters the VGPR has been found to increase linearly with increased feed concentration at low concentrations (up to about 3.5 % VS), while increases in concentration at higher levels have less effect (Gunnerson and Stuckey 1986: 131). This saturation effect results from a decrease in the bacterial growth rate at higher concentrations, which is apparently due to greater restrictions on the movement of organic material and bacteria which enables bacteria to reach undigested material (*ibid*). For the same reason the gas yield remains constant at low concentrations, but starts decreasing when the feed concentration reaches a certain level.

Hobson *et al* (1980: 246) has observed these patterns in experiments with pig manure, and found that the gas yield decreased with an increase in the TS concentration above approximately 6 %. A decrease in the gas yield has also been reported for poultry excreta at TS concentrations higher than approximately 4 % (Hobson *et al* 1980: 248) (Aubart and Fauchille 1983: 33). The decrease in gas yield at higher feed concentrations seems to be much more pronounced in the case of poultry excreta than for pig manure (Hobson *et al* 1980: 248). This has been attributed to the much higher levels of ammonia-nitrogen found in slurry from poultry excreta at high concentrations (e.g. 6-13 % TS) compared to pig manure slurry (*ibid*). By contrast, cattle manure has been digested at these high concentrations without a significant decrease in the gas yield (Hobson *et al* 1980: 248) (Dhawale and Danawade 1992: 10).

3.3.1.2 Practical considerations

The recommended slurry concentration for simple plants operated on a continuous basis vary between 4 % and 12 % TS, the most common being 8 % TS (Fulford 1988: 35) (Sasse 1988: 10) (Werner, Stöhr and Hees 1989: 40). By contrast, slurries with a TS content of up to 30 % can be digested in batch systems (Fulford 1988: 35) (see Section 3.2.1).

The maximum concentration of the slurry which can be digested in a continuously operated plant depends on a number of factors, one of which is the inlet arrangements of the plant. Simple plants are mostly fitted with an inlet pipe through which the feed material flows into the digester, while large systems may be fitted with a pump. Feed material with a TS content higher than 12 % does not flow easily through inlet pipes (Fulford 1988: 35), while the maximum TS content which allows pumping is about 10 % (Demuynck *et al* 1984: 20). According to Werner *et al* (1989: 24) no operational problems should be encountered if the TS content does not significantly exceed 10 %, while a TS content of 15 % or more would tend to inhibit the digestion process. The maximum slurry concentration also depends on the presence of toxins in the slurry. For example, in the case of poultry manure and human excreta the high nitrogen content of the substrate could result in ammonia toxicity at high feed concentrations (see Section 3.4.2).

Low slurry concentrations are also undesirable in simple biogas plants for a number of reasons. A low TS content (< 2 %) would mean that the digester volume is not utilised efficiently (Hobson *et al* 1980: 245), resulting in an increase in the cost of the energy produced. In the case of large-scale systems, this would also involve the pollution of a large quantity of water. A thin slurry is also more prone to stratification, whereby the solids with the greatest density tend to settle at the bottom, while the less dense solids (often plant matter) tend to float on top of the slurry, resulting in a liquid layer in the middle of the digester. The scum layer which forms on top of the slurry can dry out to form a solid mat which prevent gas release from the slurry and can cause blockages in the pipes (Fulford 1988: 35). However, significant stratification should not occur if the concentration of the slurry is higher than approximately 6 % TS (*ibid*).

3.3.2 Temperature

The temperature of the digesting slurry is one of the most important parameters which determine the gas production and the degree of waste stabilisation achieved in a biogas plant. Anaerobic digestion can occur within different temperature ranges, corresponding to different bacterial populations that are adapted to function optimally within each range (Van Velsen and Lettinga 1980: 117):

- the psychrophilic temperature range (10-20 °C)
- the mesophilic range (20-40 °C)
- the thermophilic range (40-65 °C)

The temperatures which are practically attainable in simple biogas plants fall within the psychrophilic and mesophilic temperature ranges, as temperatures in the thermophilic range can only be achieved with substantial heating.

3.3.2.1 Impact on digestion and gas production

Different species of bacteria achieve optimum growth and metabolic rates within specific temperature ranges (Gunnerson and Stuckey 1986: 9). Within the mesophilic range, optimum digestion occurs at about 35 °C, which seems to be determined by the requirements of the methanogenic bacteria. At temperatures below 35 °C the rates of digestion and gas production decrease with decreasing temperature, corresponding to a decrease in the metabolic and growth rates of the bacteria. At temperatures below 20 °C digestion is slow and incomplete, while it is generally satisfactory above this level (Van Velsen and Lettinga 1980: 117). Thus 20 °C constitutes the minimum temperature at which biogas plants operate reasonably well.

According to Van Velsen and Lettinga (1980: 117) temperatures in the range of 31 to 35 °C are usually preferred for digestion under mesophilic conditions, as this provides for the maximum stabilisation of the sludge, e.g. in the case of sewage sludge. However, if some of the biogas will be used to heat the biogas plant, it is necessary to give careful consideration to the selection of the operating temperature. Van Velsen and Lettinga (1980: 118) suggests that little can be gained in terms of gas production if the digester temperature is raised above 25 °C in such cases, as a saturation phenomenon comes into effect. This is evident from Figure 3.1 where the relationship between the relative gas production rate and the operating temperature is shown for pig manure (6 % TS, 15 days retention time). In order to maximise the *net* energy production of the biogas plant, i.e. the energy available for uses other than the heating of the digesting slurry, it may therefore be advisable to operate the digester at a temperature below 31-35 °C. As discussed by Van Velsen and Lettinga (1980: 118):

> From these results it can be calculated that the optimum temperature with respect to the net energy recovery is at the lower part of the mesophilic range (i.e. 27 °C - 30 °C) in case the heat requirements of a digester have to be supplied exclusively from the biogas, which can be considered as a high grade fuel. On the other hand, when sufficient waste energy is available, e.g. cooling water of a gas motor/generator set, the optimum temperature for energy recovery may be at the upper part of the mesophilic range, i.e. 40 °C, because then the maximum gas production per kg TS is obtained.

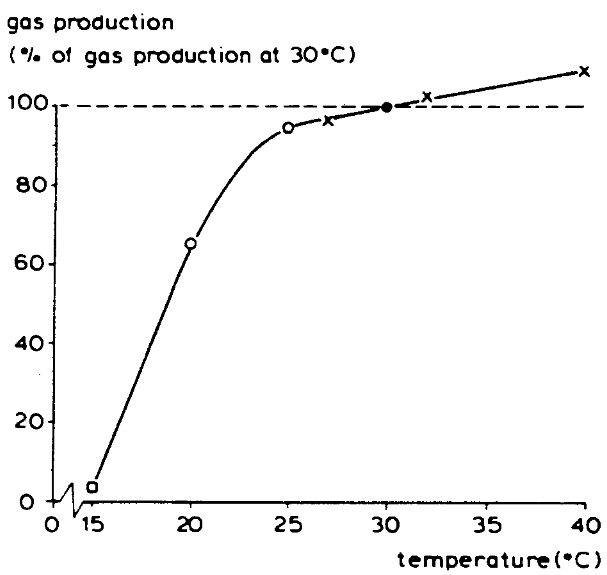

Figure 3.1: Influence of temperature on the digestion of 6 % TS pig manure slurry. (Van Velsen and Lettinga 1980: 118)

Generally the digestion process is favoured by stable temperatures as the methanogenic bacteria in particular are sensitive to changes in temperature, mainly because of their slow growth rate (Gunnerson and Stuckey 1986: 9). All the bacterial groups are fairly resilient to changes in temperature of short duration (up to about two hours), and normal gas production rates are rapidly achieved once the temperature returns to its original level (*ibid*).

However, according to Gunnerson and Stuckey (1986: 9) repeated or prolonged drops in temperature can inhibit the methanogens, and can therefore result in an imbalance in the bacterial populations. They point out that temperature variations as small as 2 °C can have adverse affects on mesophilic digestion (*ibid*), while Fulford (1988: 33) maintains that a change of more than 5 °C in a day can stop the bacteria from functioning temporarily. This view is contradicted to some extent by Van Velsen and Lettinga (1980: 119) who found that the digestion process in a laboratory-scale digester run on pig manure (15 days retention time, 6 % TS) was not seriously affected by large and repeated temperature changes between 20 and 40 °C. Nevertheless, the general principle remains that a stable temperature provides the most favourable conditions for digestion.

3.3.2.2 Practical considerations

As simple biogas plants are usually unheated, the digester temperatures tend to fluctuate with the seasonal and even daily changes in ambient and soil temperature (Werner *et al* 1989: 40). The soil temperature in particular is of importance as the digesters of simple plants are usually situated underground. According to Werner *et al* (1989: 40) the digester temperature in unheated plants is usually approximately 1-2 °C above the soil temperature. The soil temperature in an area depends on the topography, the ground cover, the type of soil and the water content of the soil. Moist soils and dark soils generally have larger temperature fluctuations because of the higher absorption of solar radiation (Werner *et al* 1989: 21). The soil temperature usually varies less than the ambient temperature, e.g. tropical soils show a nearly constant temperature at a depth of 30-60 cm (*ibid*).

While soil temperatures are not as readily available as ambient temperatures, the former can often be estimated by considering the ambient temperature. As a rule of thumb, the mean annual ambient temperature in tropical areas can be taken as the soil temperature (Werner *et al* 1989: 21). However, in a more temperate climate, such as that found in most parts of South Africa, there would be greater variation in the soil temperature. The mean ambient temperatures and mean soil temperatures at different depths at a few locations in South Africa are given in Table 3.1. From this it is evident that there is reasonable correspondence between mean ambient and soil temperatures during summer, while the soil temperature can be considerably higher than the mean ambient temperature during winter, depending on the location.

Generally speaking the temperature requirements for the application of simple biogas technology are satisfied within the tropical areas, where relatively high mean temperatures occur and daily and seasonal temperature variations become increasingly smaller towards the equator (Werner *et al* 1989: 20). However, the suitability of a specific location should be evaluated in the light of local temperature conditions, by considering both the mean annual temperature and temperature variations.

In Figure D.1 in Appendix D the different temperature zones in South Africa are shown, based on mean annual surface temperature. In addition, detailed temperature characteristics of specific locations are provided in Appendix E. Generally an area is unsuitable for the use of simple biogas plants if the mean ambient temperature is below 15 °C for a substantial length of time (Werner *et al* 1989: 20). However, this should not be seen as an absolute rule, as a potential owner of a plant could decide that the low gas production during winter can be tolerated in the light of the benefits obtained during the rest of the year. It is also possible to insulate biogas digesters sufficiently to prevent a dramatic drop in temperature during the winter period.

Table 3.1: Mean soil and ambient temperatures at a few locations in South Africa.

	Mean soil temperature (°C)			Approximate mean ambient temperature (°C)		
	January	July	Annual	January	July	Annual
Durban				24	16	21
30 cm depth	26.2	17.2	22.3			
1.2 m depth	25.3	19.7	21.9			
Nelspruit				24	15	20
30 cm depth	27.6	17.7	23.5			
1.2 m depth	26.6	19.9	23.9			
3 m depth	24.6	22.4	23.6			
Potchefstroom				22	9	17
30 cm depth	23.7	10.7	18.1			
1.2 m depth	22.7	13.6	19.0			
3 m depth	19.7	18.0	18.9			
Wepener				22	7	15
30 cm depth	23.9	10.2	17.6			
1.2 m depth	21.7	14.0	18.2			
3 m depth	19.2	17.6	18.4			

Sources: Schulze (1986); and Department of Transport (1954).

3.3.2.3 Large-scale plants

It is generally accepted that small biogas plants should be operated at ambient temperatures, as the additional investment required for heating equipment cannot be justified by the increase in gas production which can be achieved. On the other hand, it is often assumed that large-scale biogas plants should be heated in some way, even though this may increase the investment costs of a plant considerably.

During a survey conducted in Europe (Demuynck *et al* 1984: 62) it was established that 5 % of the biogas plants surveyed were operating under low-temperature conditions (< 25 °), while 12 % operated at 25-30 °C, and 64 % at 31-35 °C. Coombs (1990: 10) reported that, while most commercial digesters in the Federal Republic of Germany operated at 30-40 °C and therefore required some heating, a small number were operating at ambient temperatures (around 20 °C). This seems to indicate that the operation of large-scale biogas plants at ambient temperatures should be viable in South Africa.

3.3.3 Retention time

In simple biogas plants the retention time is a measure of the time that the slurry remains within the digester. In the case of continuous biogas plants the theoretical retention time (in days) is given by the digester volume divided by the volume of feed material added to the digester on a daily basis. The real retention time depends on the design and operation of a plant and can differ substantially from the theoretical retention time. For example, plug-flow digesters have been found to provide a real retention time which is 70 % of the theoretical retention time, compared to the 30 % achieved in mixed digesters (Tentscher 1986: 443).

3.3.3.1 Impact on digestion and gas production

The gas yield as well as the waste stabilisation achieved during the digestion process, tend to increase with increasing retention time (Aubart and Fauchille 1983: 33). The impact of retention time on the methane yield of pig manure slurry is shown in Figure 3.2. By contrast the volumetric gas production rate decreases with increasing retention time as illustrated in Figure 3.3 for poultry excreta at different slurry concentrations.

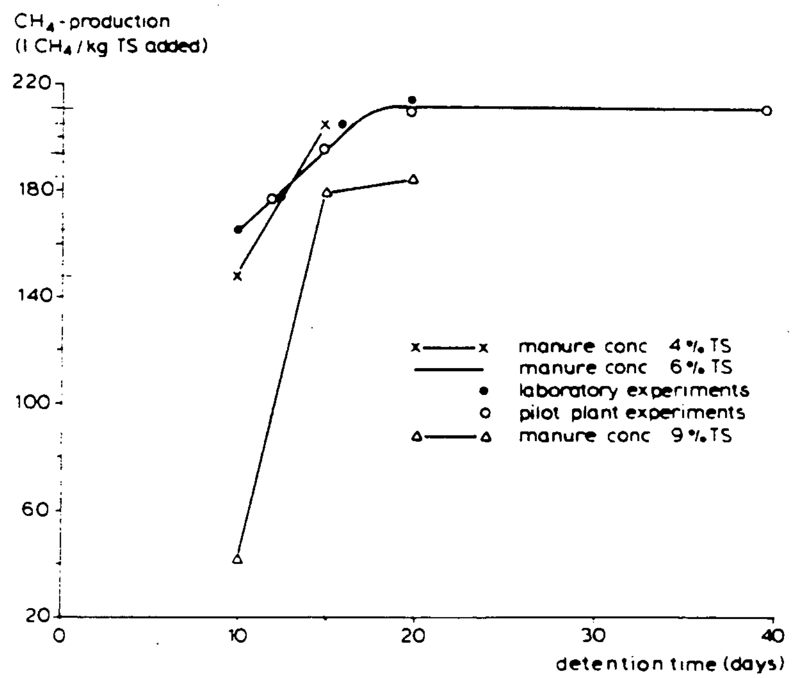

Figure 3.2: Influence of retention time on methane yield for pig manure slurry at different feed concentrations. (Van Velsen and Lettinga 1980: 115)

The recommended minimum retention time for digestion at mesophilic temperatures is 10 days as the digestion process becomes unstable at lower retention times (Kloss 1991: 6) (Van Velsen and Lettinga 1980: 113). Van Velsen and Lettinga (1980: 115) observed a critical retention time for pig slurries of 4-9 % TS which were digested at mesophilic temperatures in laboratory and pilot-plant experiments. At retention times below 15 days the methane yield increased sharply with increasing retention time, while there was only a slight increase in the methane yield above 15 days retention time (see Figure 3.2). The critical retention time was virtually independent of the slurry concentration. A similar pattern was expected for other substrates, but the critical retention time was expected to vary with the properties of the substrate (*ibid*).

A retention time of 15 days has also been recommended for the digestion of other animal manures at mesophilic temperatures (30-37 °C). Based on laboratory experiments, Aubart and Fauchille (1983: 34) concluded that a 15 day-retention time was optimum for the digestion of poultry excreta at 6 % TS and 37 °C, as longer retention times did not significantly improve the degree of waste stabilisation. Jewell, Dell'Orto, Fanfoni *et al* (1981: 124) experimented with the digestion of dairy cattle manure (10-13 % TS) in full-scale and pilot-scale plants, and found that a 15 day-retention time provided a good compromise between digester size and waste stabilisation achieved at 35 °C. On the other hand Kloss (1991: 6) recommended a retention time of 20-25 days for the digestion of pig manure (6 % TS), and 30-35 days for the digestion of cattle manure (10 % TS) at a temperature of 30 °C, based on economic considerations.

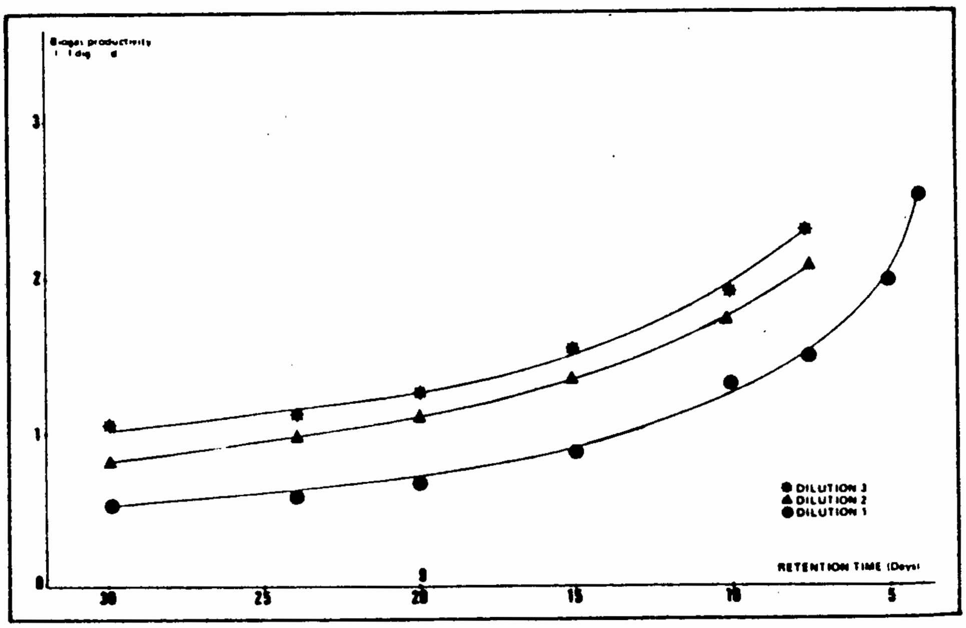

Figure 3.3: Influence of retention time on volumetric gas production rate for slurry from poultry excreta at different feed concentrations. (Aubart and Fauchille 1983: 32)

It is generally possible to achieve the same gas yields at different digester temperatures by adjusting the retention time, assuming that the other operating parameters remain constant. Kloss (1991: 6) defined a compensation factor which enables this conversion of the retention time in relation to temperature. The relationship between the relative speed of the digestion process (relative reaction speed) and the compensation factor on the one hand, and the process temperature on the other, is illustrated in Figure 3.4. The relative reaction speed and the compensation factor both have the value of one at a temperature of 30 °C. Their values at other temperatures can be obtained from the figure. For example, as the reaction speed at 20 °C is approximately half of what it is at 30 °C (i.e. the relative reaction speed is 0.5), the retention time at 20 °C has to be double the retention time at 30 °C to achieve the same gas production, corresponding to a compensation factor of two. The retention times given above for digestion at mesophilic temperatures can therefore be converted to the corresponding retention times at lower temperatures. For example, the minimum retention times which should be employed at temperatures of 20 °C and 25 °C are 20 days and 14 days respectively.

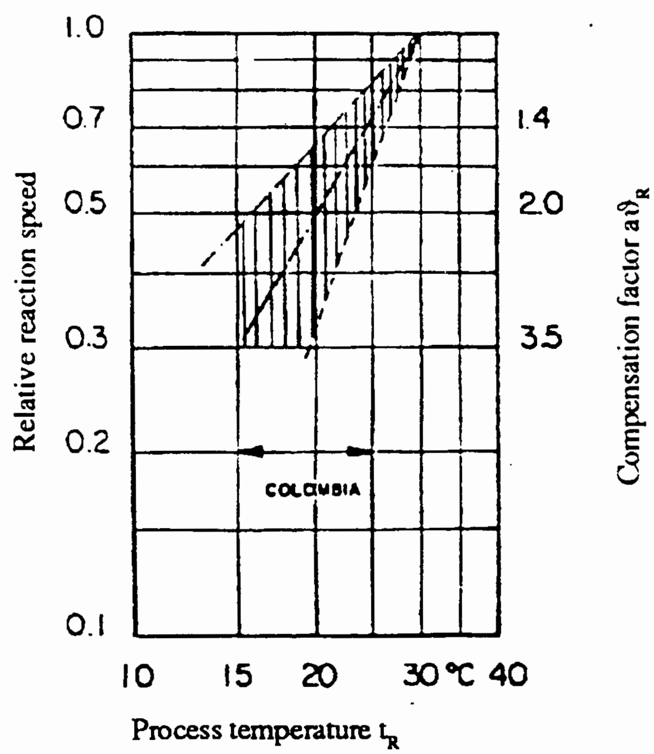

Figure 3.4: **The compensation factor which relates retention times at different temperatures. (Kloss 1991: 6)**

3.3.3.2 Practical considerations

The retention times which are generally employed in simple and relatively small biogas plants tend be much longer than those discussed above. Longer retention times are seen as beneficial in these cases, as it ensures that optimum use is made of limited quantities of substrate, it reduces the work required to feed a plant as less slurry has to be added, and it ensures that more of the pathogens in the substrate are destroyed (Sasse 1988: 9). According to Werner *et al* (1989: 23) longer retention times (i.e. up to 100 days) can also preclude scum formation and sedimentation in biogas plants.

Werner *et al* (1989: 40) recommends that a retention time of at least 40 days should be employed in simple biogas plants, but points out that retention times of 60-80 days, or even 100 days or more, are not rare where there is a shortage of substrate. Sasse (1988: 8) argues in favour of retention times of up to 90 days. Recommended retention times in different temperature ranges are given by Werner *et al* (1989: 48):

- more than 100 days at 15-18 °C
- 60-100 days at 19-28 °C
- 30-60 days at 28-33 °C

Generally larger plants are operated at shorter retention times than small plants, which show more correspondence with the recommended retention times discussed above. In the Federal Republic of Germany retention times of 20-30 days are generally used at operating temperatures higher than 25 °C (Schulz and Mitterleitner 1990: 29). However, if digestion takes place at psychrophilic (ambient) temperatures, retention times as long as 80-90 days are used in European countries (Demuynck *et al* 1984: 62).

3.3.4 Loading rate

The loading rate can be defined as the mass of TS, VS or COD added to a digester per unit volume of digester per day. It can also be expressed as the ratio between the feed concentration and the retention time. In the case of batch systems the loading rate is defined as the initial load (i.e. the mass of TS, VS or COD per unit volume of digester) divided by the number of days for which the plant will be in operation (Demuynck *et al* 1984: 61).

The effect of the loading rate on gas production is similar to that of feed concentration. The volumetric gas production rate increases with increasing loading rate and this relationship is identical at different feed concentrations (Aubart and Fauchille 1983: 33). On the other hand, the methane yield remains constant at low loading rates, e.g. up to 1 kg VS per m^3 of digester volume per day (Gunnerson and Stuckey 1986: 131). The methane yield starts to decrease at a higher loading rate, which depends on the properties of the substrate, and is much lower for insoluble substrates like agricultural wastes than for soluble substrates (*ibid*).

According to Sasse (1988: 17) 1.5 kg VS/m^3/day is a fairly high loading rate in the case of simple biogas plants, while temperature-controlled and mechanically stirred large-scale plants can be loaded at approximately 5 kg/m^3/day. Demuynck *et al* (1984: 14) recommends that the loading rate should not exceed 4 kg VS/m^3/day.

3.3.5 pH and alkalinity

The optimum pH for digesters is generally within the range of 6.8-7.2 which reflects the requirements of the methanogenic bacteria (Gunnerson and Stuckey 1986: 108). The digester pH is governed by the interaction of various acids and bases present in the slurry (*ibid*). Volatile fatty acids, such as acetate, are produced during the digestion process, and tend to lower the pH. However, a system of reactions in the digester, involving the bicarbonate ion and carbon dioxide, provides a buffering capacity to the slurry (Gunnerson and Stuckey 1986: 8). Higher concentrations of bicarbonate in the slurry provide for a greater buffering capacity and therefore greater resistance to changes in the pH. According to Demuynck *et al* (1984: 9) a concentration range of bicarbonate between 2 500 and 6 000 mg/ℓ usually provides sufficient buffering capacity.

The alkalinity of the slurry, which is measured in milligrams of calcium carbonate per litre of slurry, also serves as an indicator of the buffering capacity available. Generally the buffering capacity would be sufficient if the alkalinity is above 1000 mg/ℓ of $CaCO_3$ (Rivett-Carnac 1982: 74). A drop in pH below 6.8 is an indication of acid build-up in the slurry (Gunnerson and Stuckey 1986: 13), which could result from sudden changes in the operating conditions. For example, if the feeding rate of the digester is suddenly increased sharply ("shock-loading"), the growth rate of the bacteria would tend to increase. As the methanogens has the lowest growth rate and are slower to adapt to changes, they would be unable to utilise all the acids formed by other bacterial groups, and these acids would tend to accumulate in the slurry. A sudden temperature drop, or the introduction of a toxin could also have this effect (Gunnerson and Stuckey 1986: 110).

The bicarbonate system typically provides a buffering capacity until a pH of approximately 6.3 is reached (Gunnerson and Stuckey 1986: 109). If excessive acid production is allowed to continue beyond this, the buffer capacity will become exhausted and the drop in pH will accelerate, thereby severely inhibiting the growth rate of the methanogens (*ibid*). The resulting "unbalanced" digester conditions would need to be rectified by introducing operational changes.

3.3.5.1 The effect of toxins

Toxic compounds can either inhibit bacteria at low concentrations or poison/kill them at high concentrations (Gunnerson and Stuckey 1986: 12). The methanogens are generally the most sensitive to toxins, although all the bacterial groups involved in digestion can be affected (*ibid*). According to Gunnerson and Stuckey (1986: 111) the toxicity threshold can be defined as

> ... the concentration of a substance at which there is a significant reduction in the rate of methane production from a balanced [bacterial] population, as compared with a control culture to which the substance has not been added.

Substances most toxic to the bacteria, i.e. with the lowest toxicity thresholds, include antibiotics and various organic compounds, followed by volatile fatty acids and synthetic detergents (Gunnerson and Stuckey 1986: 112). Heavy metals have moderate threshold levels, while sulphides, ammonia and minerals such as calcium and magnesium are least toxic (*ibid*).

It has been found that continuously operated digesters are capable of tolerating much higher levels of toxic substances than batch systems, due to a process of acclimatization of the bacterial populations (Gunnerson and Stuckey 1986: 111). This can be achieved by slowly increasing the concentration of the toxic substance, rather than "shocking" the system by increasing the concentration suddenly (*ibid*). However, because of the low growth rate of methanogenic bacteria, this can be a time-consuming process (Van Velsen and Lettinga 1980: 114). According to Gunnerson and Stuckey (1986: 110) toxicity is not a common problem in digesters which utilise natural substrates such as agricultural wastes, which is the focus of this study. The major toxicants which are encountered in these digesters are ammonia, volatile fatty acids and heavy metals (Gunnerson and Stuckey 1986: 12).

Ammonia toxicity can be encountered if feed materials with a high nitrogen content are used, such as poultry and human excreta (see Section 3.4.2). According to Gunnerson and Stuckey (1986: 112) free ammonia is more toxic to the bacteria than ammonium ion, with the result that ammonia toxicity thresholds are very sensitive to the pH of the slurry. For example, an ammonia-nitrogen concentration of 3000 mg/ℓ was found to inhibit digestion at any pH, while concentrations below 3000 mg/ℓ were inhibitory only at pH levels of 7.4-7.6 (Hobson *et al* 1980: 248). On the other hand, with a process of acclimatization, it has been possible to achieve stable digester operation at ammonia-nitrogen concentrations as high as 8000 mg/ℓ (Gunnerson and Stuckey 1986: 112).

High concentrations of volatile acids are associated with toxicity effects, with the toxicity threshold being reported as 3000 mg/ℓ (Rivett-Carnac 1982: 74). However, it has been found that relatively large concentrations of these substances (e.g. 6000 mg/ℓ or more) can be present without inhibiting digestion, provided that the digester pH is neutral (Gunnerson and Stuckey 1986: 111).

3.4 Substrate characteristics

In addition to the various operational parameters, the characteristics of the organic substrates which are utilised in biogas plants also have an important impact on digestion and gas production. In this section the biodegradability as well as the carbon to nitrogen ratio of substrates are considered. Other properties of substrates such as animal manure and plant matter will be discussed in Section 6.2.

3.4.1 Biodegradability of the substrate

According to Gunnerson and Stuckey (1986: 118) the biodegradability of a substrate is usually measured as the percentage of COD which is removed or the percentage of VS destroyed in the digestion process. They point out that biodegradability needs to be normalised in terms of retention time, as a typical digestion process may achieve 80 % reduction in the organic content in 15 days, 90 % in 30 days and 95 % in 120 days (*ibid*). The ultimate biodegradability of a substrate is therefore defined as the gas yield which is achieved if the substrate is digested for a period approaching infinity (Gunnerson and Stuckey 1986: 124).

The biodegradability of a substrate depends on its chemical structure and composition (Gunnerson and Stuckey 1986: 131), both of which play an important role in this regard:

> The main digestible components of solid wastes are carbohydrates (cellulose and hemicellulose), proteins and fats. Although these components in themselves are well digestible (except perhaps lipid material) they can be present in wastes in such a structural form that they are not easily available for biodegradation. This holds for coagulated and fibrous proteins, e.g. hairs, and the cellulose and hemicellulose incorporated in a lignin complex. (Van Velsen and Lettinga 1980: 113)

Lignin in particular has an important impact on the biodegradability of substrates. It is virtually undegradable by anaerobic processes, and, as illustrated above, it also inhibits the digestion of the carbohydrates with which it is linked (Gunnerson and Stuckey 1986: 119). As lignin is an important structural component of plants, it has a significant effect on the overall biodegradability of most agricultural substrates, which generally contain plant matter either directly (e.g. crop residues) or indirectly (e.g. animal manure) (*ibid*).

Generally the degradability of animal manures is dependent on the diet of the animals. A significant variation (30-70 %) has been observed in the degradability of cattle manure (Gunnerson and Stuckey 1986: 119), which can be explained to some extent by the lignin content of the cattle feed: In developed countries the feed given to cattle has a high protein content and a low lignin content so that the manures are highly degradable. On the other hand, cattle in underdeveloped countries are mostly fed agricultural residues with a high lignin content, resulting in less degradable manures (Gunnerson and Stuckey 1986: 119). According to Jewell *et al* (1981: 121) the primary reason for the variation observed in the biodegradability of dairy manure (40-65 % of VS destroyed) appeared to be the variation in the diet of the animals. A related factor which appears to influence biodegradability is the degree to which a substrate can be made soluble. For example, insoluble sludge and animal wastes are generally only 40-60 % degradable (Gunnerson and Stuckey 1986: 119). It has also been found that the degradability of cattle manure is higher if it is fresh (*ibid*).

Biodegradability varies considerably for different substrates (Gunnerson and Stuckey 1986: 131). The following figures for the biodegradability of different animal manures are reported by Jewell *et al* (1981: 114):

dairy cattle manure:	35 % of volatile solids destroyed
beef cattle manure:	50 % "
pig manure:	55 % "
poultry excreta:	65 % "

A few authors have reported figures on the digestion achieved in simple biogas plants with no reference to particular substrates. In India 30-50 % of the organic component of substrates is reportedly digested in both fixed-dome and floating-drum plants, whether operated on manure or plant wastes (Renewable Energy Resources Information Center 1987: 4). According to Sasse (1988: 17) about 50 % of the substrate is fully digested in simple biogas plants.

The biodegradability of a substrate has an important impact on gas production. According to Gunnerson and Stuckey (1986: 121) significant increases in gas yield can be achieved by improving the biodegradability of agricultural substrates.

3.4.2 Carbon to nitrogen ratio of the substrate

According to Gunnerson and Stuckey (1986: 12) the nutrient requirements of anaerobic bacteria are generally relatively simple. The methanogenic bacteria are the most severely inhibited by slight nutrient deficiencies. While this is seldom a problem in the case of complex substrates such as animal manure, it is often necessary to add nutrients to the digester when simple substrates such as crop residues are digested, to enable the growth of the bacteria (*ibid*). On the other hand, an essential nutrient can become toxic to the bacteria if its concentration in the substrate is too high (Gunnerson and Stuckey 1986: 12).

It is particularly important to ensure that the *nitrogen* content of the substrate is maintained at an optimal level to provide for good digestion without risking toxic effects (Gunnerson and Stuckey 1986: 13). The carbon to nitrogen (C/N) ratio of the substrate was found to be a useful parameter for this purpose, and a C/N ratio of 30 is often cited as the optimum for efficient digestion (*ibid*). In order to provide a meaningful interpretation of this value, a distinction needs to be made between the overall C/N ratio of a substrate, and the C/N ratio involving the quantities of carbon and nitrogen that are actually available for digestion. The optimum value refers to the latter, which depends on the characteristics of the substrate as well as operational parameters (*ibid*). On the other hand, it has been found that efficient digestion can occur at *overall* C/N values which range from less than 10 to more than 90 (Gunnerson and Stuckey 1986: 13). According to Werner *et al* (1989: 47) a C/N ratio of less than eight, e.g. in the case of human excreta and poultry excreta, may lead to excessive levels of ammonia in the slurry.

3.5 Calculation of expected gas production rates

Some information is presented in this section which can be used to calculate expected gas production rates for simple biogas plants operated on a continuous basis. The most useful information for this purpose, which enables the calculation of gas production rates at different temperatures and retention times, was obtained from Werner *et al* (1989: 24) and Sasse (1988: 20). The mean gas yield values for different types of substrate, which are presented in Table 3.2, and the relative gas yield curves for the conversion of the mean values to gas yields at specific temperatures and retention times (see Figure 3.5), were provided by Werner *et al* (1989: 24). In addition, Sasse (1988: 20) presented the two graphs shown in Figures 3.6 and 3.7, which provide gas production rates (measured in litres of biogas per kilogram of fresh manure added per day) at different temperatures and retention times for fresh cattle manure (approximately 16 % TS) and fresh pig manure (approximately 17 % TS) respectively.

Table 3.2: Mean gas yields for different substrates.

Substrate	Biogas yield (ℓ/kg VS added)	
	range	average
pig manure	340-550	450
cow manure	150-350	250
poultry manure	310-620	460
horse manure	200-350	250
stable manure	175-320	225
sheep manure	100-310	200
grain straw	180-320	250
corn straw	350-480	410
rice straw	170-280	220
grass	280-550	410
elephant grass	330-560	445
vegetable residue	300-400	350
water hyacinth	300-350	325
algae	380-550	460
sewage sludge	310-640	450

Source: Werner *et al* (1989: 24).

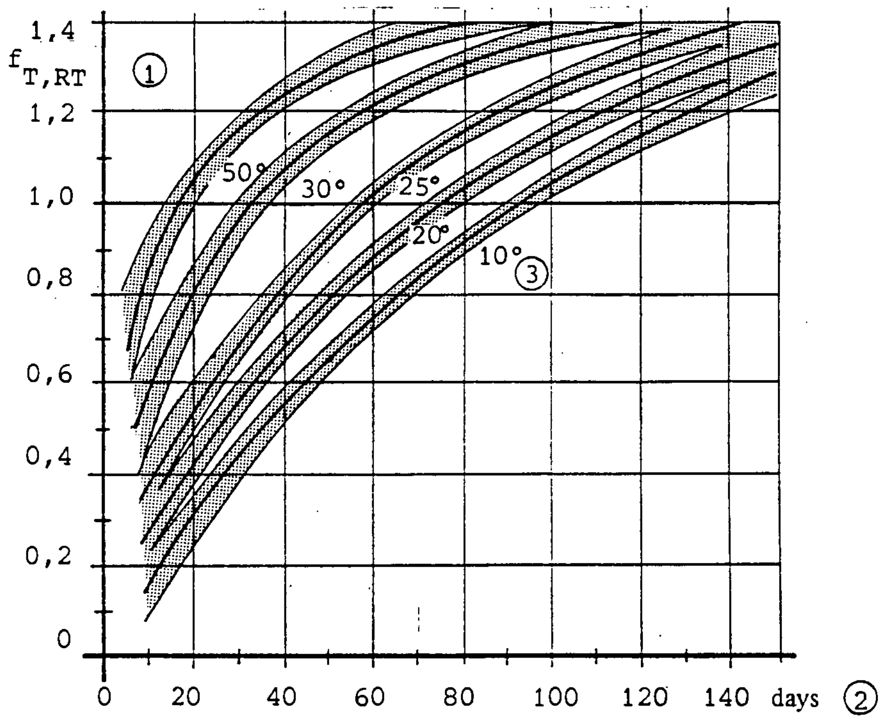

Figure 3.5: Relative gas yield curves for the conversion of average gas yields to yields at different retention times and temperatures. (Werner *et al* 1989: 48)

However, a substantial difference has been found between the calculated daily gas production rates at a temperature of 20 °C, using the information from the two sources. The calculated gas production rates for cattle manure at 50-70 days' retention time, using the information provided by Werner *et al* (1989), are 28-36 % higher than the corresponding rates based on Sasse's (1988: 20) information. Similarly differences of 35-39 % were found for pig manure. It is therefore probably advisable to adjust calculated gas production rates which are based on the information provided by Werner *et al* (1989) accordingly, particularly at lower temperatures.

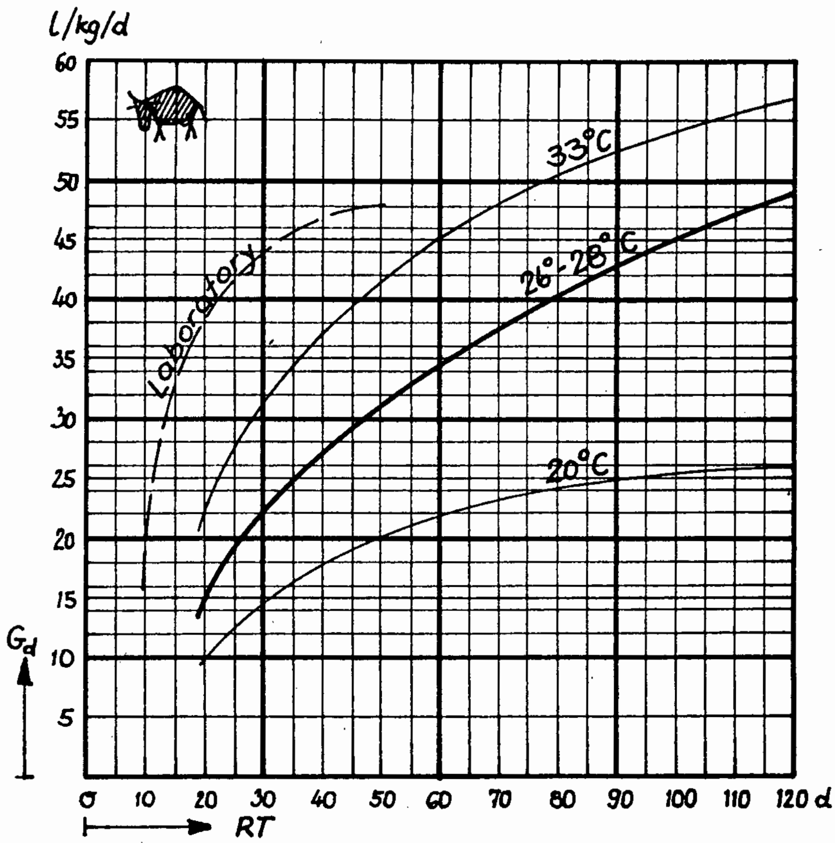

Figure 3.6: Gas production rates (per kilogram of fresh manure) for cattle manure at different retention times and digester temperatures. (Sasse 1988: 20)

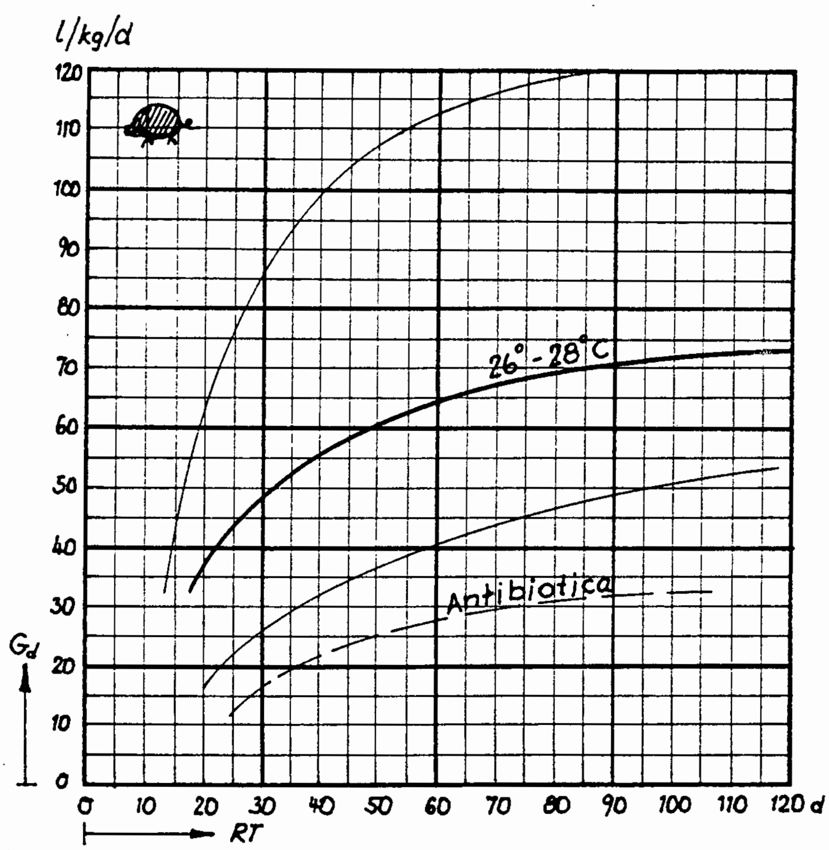

Figure 3.7: Gas production rates (per kilogram of fresh manure) for pig manure at different retention times and digester temperatures. (Sasse 1988: 21)

3.6 Conclusions

Biogas plants can be operated as batch systems or continuous systems. This study has mainly been concerned with biogas plants which are operated on a semi-continuous basis, i.e. where the fresh slurry is added regularly but not continuously, e.g. once a day.

The most important function of biogas plants which has been considered here, is the production of biogas for energy purposes. Gas production can be expressed in terms of the volume of the biogas plant (i.e. the volumetric gas production rate) or the mass of solids added to the plant (i.e. the gas yield). The gas production achieved in a biogas plant depends on the characteristics of the substrate as well as various operational parameters.

The concentration of the slurry in simple biogas plants which are operated on a continuous basis, should generally be between 6 % and 13 % total solids, depending on the type of substrate used. Substrates with a low carbon to nitrogen ratio, such as poultry excreta, need to be diluted more to prevent ammonia toxicity in the digester, while cattle manure can be digested successfully at a total solids concentration of 13 %. Simple biogas plants are generally operated at ambient temperatures. As digestion becomes unsatisfactory below 20 °C, an area is generally only suitable for the implementation of simple biogas technology if the mean ambient temperature does not remain below 15 °C for a substantial length of time. Large-scale biogas plants can also be operated satisfactorily at relatively low temperatures, as has been done in some European countries. Similar gas yields can be achieved in digesters which are operated at different temperatures, if the retention time of the digester at the lower temperature is suitably increased. Small-scale biogas plants are generally operated at retention times of 60-80 days and even longer, for reasons such as the small quantities of substrate available.

The optimum pH for digesters is generally within the range of 6.8-7.2. A drop in pH below 6.8 is an indication of acid build-up in the slurry, which could result from sudden changes in the operating conditions, such as the temperature, or the presence of toxins in the slurry. However, toxicity is not a common problem in digesters which utilise natural substrates such as agricultural wastes. Substrates with a C/N ratio less than eight, e.g. human excreta and poultry excreta, may lead to excessive levels of ammonia in the slurry, which is toxic to the bacteria.

CHAPTER 4

DESIGN AND CONSTRUCTION OF BIOGAS PLANTS

4.1 Introduction

A large number of simple biogas plant designs are currently available around the world, but many of these are variations of a few basic types. This study focused mainly on small-scale biogas plants (i.e. digester volumes of the order of 10 m^3) which can be utilised by single households to provide energy for domestic purposes. The two designs which are most suitable for this purpose are the floating-drum and the fixed-dome plants, which are widely used in countries such as China and India. Some consideration was also given to biogas plants which are suitable for large-scale agricultural applications. The flexible cover biogas plant is particularly suitable for this purpose, and has been used successfully in countries such as Taiwan and the United Sates of America (Fulford 1988: 52) (Jewell *et al* 1991: 130).

These three biogas plants will be discussed in some depth in this chapter, including aspects of the design, operation and construction of each system. The pilot plants that were built during this study will be considered in particular, as the installation of these plants provided the opportunity to test some design aspects and to evaluate the different designs. Although only a small number of plants was installed during this study, it has been possible to build at least one of each of the designs considered here. The costs of the pilot plants have been analyzed and the results are presented in the final section of this chapter. Photographs of the pilot plants are provided in Appendix C.

4.2 The floating-drum biogas plant

This plant comprises a digester in the form of a pit filled with slurry and a floating cylindrical gas drum in which the gas is collected (see Figure 4.1). It can be built up to digester sizes of 100 m^3 (Werner *et al* 1989: 62), although the gas drum presents some difficulties in large plants. It is usually operated on a semi-continuous basis with fresh slurry being added regularly but not continuously, e.g. once a day. Fresh slurry is mixed in a mixing box and enters the plant through an inlet pipe. When fresh slurry is added to the plant, roughly the same quantity of digested slurry leaves the digester through an outlet pipe and is stored temporarily in a collection box. The operating principle can therefore be described as "flow-through". The level of the slurry in the digester is determined by the level of the outlet pipe or the overflow. A baffle wall may be built inside the digester to prevent the short-circuiting of fresh slurry to the outlet pipe.

The gas pressure is determined by the weight of the gas drum and remains constant as the gas drum moves up and down to accommodate changes in the gas volume. The gas pressure tends to be fairly low (of the order of 10 cm water pressure), but can be increased by placing weights onto the drum. The drum is centred in the digester and prevented from tilting by means of a guide system. Some means of support is provided to the drum at its lowest position in the digester. A ring-shaped gas deflecting ledge is provided on the inside of the digester below the gas drum to prevent large quantities of gas from escaping through the annular gap between the digester walls and the gas drum.

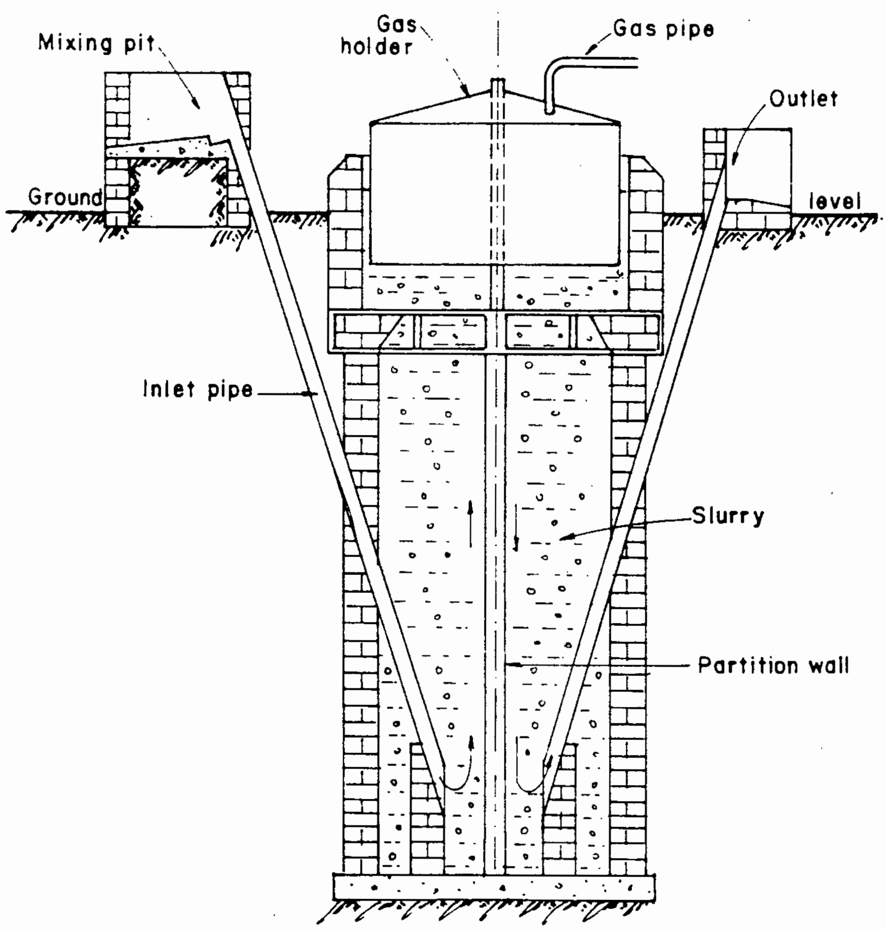

Figure 4.1: A floating-drum biogas plant. (United Nations 1980: 13)

According to Werner *et al* (1989: 62) animal manure and human excreta are generally used as feed materials in floating-drum plants, while vegetable waste can also be added. Fibrous materials such as crop residues can only be used in a floating-drum plant which is fitted with a water-jacket (see Section 4.2.3), as the gas drum tends to get stuck in the thick layer of floating scum that forms on the slurry when these materials are used. This was observed in one of the plants that was built as part of this study (see Section 8.4.4).

The physical operation and utilisation of the plant is very simple. Blockages inside the plant are immediately evident if digested slurry does not leave the digester when fresh material is added. In addition, the volume of gas available is clearly visible from the height of the gas drum. The visible nature of the operation of the plant is a major advantage when biogas plants are utilised by people who are not able to grasp the operational complexities fully. The main advantages of this design are therefore that it is easy to understand and operate, in addition to being relatively easy to build. It is recommended by Werner *et al* (1989: 54) as a mature, effective technology, which is particularly suitable where reliability is regarded as more important that cost savings.

For these and other reasons, particularly the difficulties associated with the construction of the fixed-dome plant (see Section 4.3), it was decided to focus on the floating-drum plant rather than the fixed-dome plant in this study. This decision was particularly influenced by the experience of the Rural Industries Innovation Centre (RIIC) at Kanye in Botswana, which the author had visited during May 1990. The RIIC decided to develop the floating-drum plant for use in Botswana after attempts to build the fixed-dome plant successfully had failed. The floating-drum plant has subsequently been recommended to the author by a number of people who have experience in biogas technology, including Professor Hutcheon of the National University of Lesotho[7], who conducted a biogas research project in that country (Hutcheon 1986).

Two floating-drum plants were constructed as part of the study, the first at the homestead of the Mathabela family in Gazankulu, and the second at the experimental farm of the University of Pretoria (see Sections 8.2 and 8.4 respectively). The discussion that follows will focus on aspects of the design and construction of floating-drum biogas plants, with specific reference to the plants that were built as part of this study. Different digester designs are considered, as well as alternative ways of constructing the gas drum. Design drawings of the completed demonstration units are provided in Appendix B.

4.2.1 The floating-drum plant with a cylindrical digester

The cylindrical digester has been used extensively in India, where deep narrow pits (up to 5 m in depth) have been favoured to reduce the diameter of the gas drum required (United Nations 1980: 111). These digesters are most often built of bricks. Generally construction becomes increasingly difficult and even dangerous as the depth of the pit increases, because of the depth of the hole that is required, as well as the height of the pit walls. Gas production is also said to be negatively affected by the high pressure in the bottom half of a deep digester (Kijne 1984: A20).

A cylindrical ferrocement digester has been built at the Mathabela homestead (see Figure C.1 in Appendix C). A mould or formwork was used, comprising corrugated galvanised iron sheets that were rolled to the correct diameter (Watt 1978: 49) (see Figure C.2 in Appendix C). Chicken wire mesh and cold drawn fencing wire were wrapped around the mould before plastering commenced[8]. The digester built at the Mathabela homestead is 3 m deep and therefore required a 3 m-high mould for construction. Although the mould was somewhat awkward to handle and transport, it did not present major difficulties during

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[7]Personal communication with Professor Hutcheon in April 1991.

[8]This technique has been used for water tank construction in the rural areas of South Africa by organisations such as World Vision, Operation Hunger and The Valley Trust.

construction. However, based on practical considerations, it is recommended that this technique should not be used for the construction of digesters to a depth greater than 3 m.

The size of the cylindrical ferrocement digester is further restricted by considerations regarding the dimensions of the gas drum. The cost of the drum increases as its diameter to height ratio increases beyond $\pm$ 2, while the gas pressure it is able to provide also decreases. The recommended maximum size of a cylindrical ferrocement digester of 3 m depth is therefore approximately 10 m^3, which corresponds to a digester diameter of approximately 2.15 m.

A mild steel gas deflecting ledge was installed in the Mathabela biogas digester approximately one year after its construction. It comprises a ring cut of mild steel plate which rests on steel nails fixed into the digester wall. This is not regarded as a satisfactory option in general, as it would probably need to be replaced after a few years due to corrosion. However, difficulties had been experienced with the construction of a ferrocement ledge when the plant was built. A ferrocement ledge can be built by fixing a metal framework to the inside of the incomplete digester wall and plastering over it when the inside of the digester is plastered. A baffle wall inside the ferrocement digester divides it into two more or less equal compartments. The wall prevents the short-circuiting of fresh slurry inside the digester, and serves to support the gas drum at its lowest position.

The inlet and outlet pipes through which slurry enters and leaves the digester are made of PVC. Special measures are required when PVC pipes are fitted into a ferrocement wall, as very little bonding occurs between PVC and cement. When the plant at the Mathabela homestead was built, the inlet and outlet pipes were fitted through holes that were made in the completed digester walls, and the joints simply covered with plaster. This proved inadequate on the outlet side, where the joint was subsequently reinforced by means of a concrete apron around the pipe. The joint would be of adequate strength if chicken wire mesh is wrapped around the pipe where it intersects the wall, and then tied to the reinforcement that protrudes from the wall, before the joint is plastered.

4.2.2 The floating-drum plant with a tapered digester

As discussed above, the simple ferrocement technique which utilises a cylindrical mould is only suitable for the construction of digesters to a maximum size of 10 m^3. It was therefore decided to build a digester which is suitable for larger sizes at the experimental farm of the University of Pretoria (UP). This plant is shown in Figure C.5 in Appendix C. A digester with a tapered form was chosen, i.e. one with a diameter which is larger at the bottom than at the top (see design drawings in Appendix B). It is similar to a digester which has been developed in Nepal (Fulford 1988: 45). A tapered digester requires a shallower hole than a cylindrical digester of the same size. It is therefore suitable for the construction of small plants (smaller than 10 m^3) in areas with a high water table or with a shallow rock-layer, as well as for the construction of plants larger than 10 m^3.

The digester was built of bricks, as this provided the easiest option for building the tapered part of the digester. In addition, bricks and brick-laying skills are fairly widely available in South Africa. The tapered part of the digester was built by reducing the diameter of each consecutive layer of bricks by a fixed amount. The gas deflecting ledge was built as an integral part of the digester and it also serves as support for the gas drum at its lowest position. A baffle wall has not been provided, as the digester is fitted with an overflow rather than an outlet pipe as was the case with the digester at the Mathabela homestead (see Section 4.2.10).

4.2.3 The floating-drum plant with a water-jacket

A floating-drum plant with a water-jacket is illustrated in Figure 4.2. It differs from the digester designs discussed above in that the drum is not in direct contact with the slurry, but moves up and down in a circular channel that is filled with water.

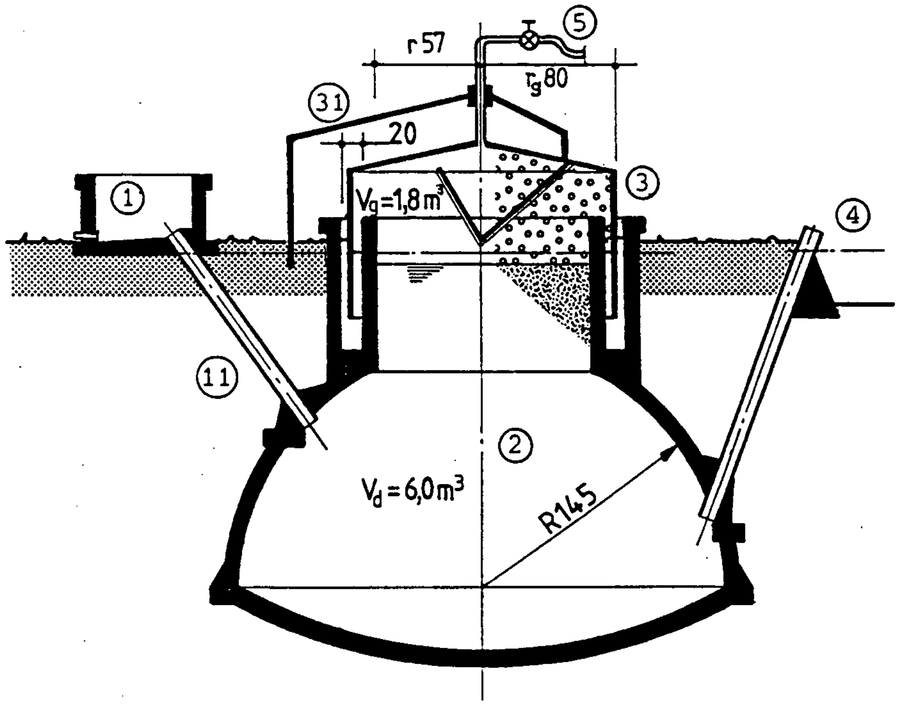

Figure 4.2: A floating-drum plant with a water-jacket. (Werner *et al* 1989: 54)

The water-jacket design has wider applicability than the other digester designs. As the slurry is completely enclosed, it is particularly suitable for the digestion of human excreta, while fibrous material can also be digested in the plant. It would be somewhat more expensive to build than the other designs, but a metal gas drum used on this digester should last longer as a result of the reduced corrosion (Werner *et al* 1989: 62).

The water-jacket plant generally has a more aesthetic appearance than the other floating-drum plants, particularly as the gas drum remains relatively clean. It also provides for the collection of all the gas which is formed, compared to the other designs where some gas escapes through the annular ring between the digester and the gas drum. However, gas has been found to leak through the brick structure which is in contact with the gas space (Kijne 1984: A21). The water-jacket plant is regarded by Werner *et al* (1989: 62) as the most reliable of all the available biogas plant designs.

The tapered brick digester that was built at the University of Pretoria (see Section 4.2.2) can be provided with a water-jacket relatively easily by building a second half-brick wall around the cylindrical part at the top of the digester.

4.2.4 A mild steel gas drum

A mild steel gas drum comprises mild steel plates of 2-2.5 mm thickness which are welded onto an angle-iron frame. It is the most widely used gas drum design, e.g. it has been used extensively in India where the floating-drum design was developed (Fulford 1988: 43). A mild steel gas drum was used on the Mathabela biogas plant mainly as it was the most reliable gas drum design available at the time (see Figure C.1 in Appendix C).

A fairly high degree of technical skill is needed to build the mild steel drum, e.g. there is a need for high-quality welding to prevent gas leaks. In addition, cutting, bending and welding equipment are required for its construction, all of which are not commonly available in rural areas. This is an important consideration, as it is unlikely that the manufacturing of these drums at large distances from plant sites will be feasible. In India, for example, the manufacturing of gas drums at workshops in urban areas has resulted in high transportation costs as well as organisational problems when the drums have to be delivered to plant sites (Kijne 1984: A20).

A number of vertical bars were fitted inside the drum to provide for the breaking of the scum on the slurry when the drum is rotated. A paddle stirrer was also fitted through the gas drum to enable some degree of mixing of the digesting slurry. However, it is unlikely that the increase in gas production that results from the limited stirring provided would justify the additional complexity and costs of adding the stirrer. The drum was painted on the inside and outside with a primer as well as two coats of bitumen paint to protect it against corrosion. The use of high quality epoxy paint could increase the lifetime of the drum by five years (Kijne 1984: A21). The weight of the drum provided a gas pressure of 75 mm water gauge at the plant.

The mild steel drum was fairly expensive, accounting for approximately 37 % of the costs of the Mathabela family plant (see Section 8.2.4). However, as the drum had been oversized somewhat, it was more expensive than it could have been. In addition, a mild steel drum is fairly expensive to maintain as it requires annual repainting to ensure an estimated lifetime of 8-12 years (Werner *et al* 1989: 71). Moreover, the weight of the drum can present difficulties during its installation and removal. For example, eight people were required to install the drum on the Mathabela family plant. For these reasons it is not recommended for large digesters, as the repairs and replacement of the drum would be difficult and costly.

Because of these concerns regarding the mild steel gas drum, some consideration was given to alternative materials for the construction of the gas drum. These are discussed in the sections that follow. It was also decided to use the experimental plant installed at the University of Pretoria for the testing of alternative designs of the gas drum. The ideal gas drum would be inexpensive and easy to handle, with a long lifetime and little need for maintenance. It would therefore need to be corrosion-resistant as well as UV-stabilised.

4.2.5 A galvanised iron gas drum

Galvanised iron has been used for the manufacturing of gas drums in a few countries (Kijne 1984: A22). Two alternatives are available, the first being to manufacture a gas drum from corrugated sheets, similar to the manufacturing of water tanks. The galvanised iron drum would be less costly than the mild steel drum discussed above, while it would also be easier to handle than the latter because of its lower weight. However, for the same reason it would require additional weights to provide the gas pressure required. The main reservation concerning this option is the fact that the iron sheeting which is used for this purpose generally has a thickness of only 0.6 mm, which would make such a drum extremely susceptible to corrosion. A galvanised iron gas holder made of 0.6 mm-thick corrugated sheeting and covered with a rubber layer was to have been tested as part of the biogas plant at a school in KwaNdebele (see Section 8.3.3). However, this was not possible as the biogas system operated for a very short period only, while the drum delivered by the manufacturer had not been made to specifications (see Figure C.4 in Appendix C).

A second possibility for the manufacturing of a galvanised iron gas drum is to construct it from flat galvanised sheets of 2.5 mm thickness. In this case the thickness of the sheets should ensure that the lifetime of the drum is comparable to that of a mild steel gas drum. Such a drum could be built in most rural areas, as soldering rather than welding would be used to join the sheets. In South Africa rural entrepreneurs have been trained successfully in the manufacturing of galvanised iron items[9].

However, the use of galvanised iron for the manufacturing of gas drums does not provide a satisfactory alternative to the use of mild steel. It fails to address the main problem associated with the mild steel gas drum, namely the fact that it is prone to corrosion and therefore requires regular maintenance and replacement after a few years.

[9]Personal communication with Johann Rissik, Northern Transvaal Director of Operation Hunger.

4.2.6 A ferrocement gas drum

Gas drums manufactured of ferrocement have been developed in India and were found to be cheaper to construct than mild steel drums (Kijne 1984: A22). In addition, the high resistance to corrosion of ferrocement meant that extensive maintenance was not required. As ferrocement is porous to gas, the drums require gas-tight linings of bitumen or epoxy paint.

However, ferrocement gas drums are unlikely to be applicable in rural areas as considerable skill is required for their construction, while the weight of these drums can be excessive (*ibid*). This is illustrated by the fact that the gas pressure in a ferrocement drum can reach 200 cm water gauge (Kijne 1984: A23) as compared to the 10 cm water gauge typical in the case of a mild steel drum. In addition, the material is very brittle and therefore prone to cracking, while repairs are difficult (*ibid*).

4.2.7 An asbestos cement gas drum

It was decided to investigate the suitability of asbestos cement as gas drum material, as it was seen to provide the same benefits as ferrocement, with the added advantage that water tanks made of this material are fairly widely available in South Africa. The total cost of the gas drum over its lifetime was expected to be lower than that of a mild steel drum, because of the longer expected lifetime and the reduced maintenance requirements. However, there was some concern about the brittle nature of asbestos cement.

A 4500 ℓ asbestos cement water tank was found to have a suitable diameter to serve as gas drum on the plant at the UP. However, it had to be cut in half as the sides were twice the required height. A gas outlet was provided in the form of a hole in the centre of the roof into which a galvanised iron pipe was fitted. The galvanised iron pipe also provided for the guiding of the drum (see Section 4.2.9). This gas drum is shown in Figure C.5 in Appendix C. The drum was painted on the inside with bitumen paint to render it gas-tight. It was installed with some difficulty because of the weight, requiring about six people to lift the drum.

At a later stage (see Section 8.4.4) angle-iron cross bars were attached to the bottom of the drum to act as scum breakers. Handles were also attached to the sides of the drum on the outside to provide for easier installation and removal. While this was in progress, the drum fell over by accident, resulting in a cracked roof. The crack was subsequently repaired by bolting metal plates to the roof on the inside and outside. However, this incident clearly illustrated the risks associated with the use of an asbestos cement gas drum.

After the drum had been installed once more, checks revealed a number of gas leaks where bolts pierced the drum wall, even though these had been sealed as well as possible. The most significant leaks were found where the handles were attached to the gas drum and were not associated with the crack in the roof. After numerous attempts to seal the leaks, which proved to be unsuccessful, the drum was discarded. This experience has lead to the conclusion that asbestos cement is not particularly suitable as material for a gas drum.

4.2.8 A high-density polyethylene gas drum

When the asbestos cement drum on the experimental plant at the UP had to be discarded, it was decided to replace it with a UV-stabilised high-density polyethylene (HDPE) drum, as this material seemed to fulfil all the requirements for a gas drum (see Section 4.2.4). A gas drum was obtained by cutting in half an HDPE water tank of a suitable diameter.

The HDPE drum had to be modified a number of times as problem-free operation was not achieved immediately. The guiding of the drum presented the biggest problem, particularly as the digester had been provided with an external guide system suitable only for a rigid gas drum (see Section 4.2.9). Eventually both the drum and the guide system had to be modified considerably to solve the problem. The drum was provided with a metal frame, comprising two circular steel bands at the bottom and the top of the drum with four steel channels attached vertically to the steel bands (see Figure C.6 in Appendix C). Small wheels attached to the top of the digester wall guided the drum by running along the steel channels on the drum frame as the drum moved up and down. The weight of the metal framework together with additional weights placed on the drum provided a gas pressure of 75 mm water gauge at the plant.

An external guide system such as the one described here, would be a necessity if a digester with a water-jacket is installed, as it would be very difficult to guide the HDPE drum by means of an internal guide system in such a case (see Section 4.2.9). However, in general it should be possible to guide an HDPE drum by means of an internal guide system, if a rigid pipe is fitted at the centre of the drum and supported by cross-bars which are fixed to the bottom of the drum, in a manner similar to the design of the mild steel gas drum (see Appendix B for drawings). It would probably still be necessary to provide a circular steel band at the bottom of the drum to ensure that it is sufficiently rigid. This guide system would need to be tested to confirm its satisfactory performance.

Some difficulties were experienced with leaks at the gas outlet socket on the gas drum which could not be sealed properly. This occurred after the original socket was replaced, and the high frequency welding equipment that was required to ensure proper sealing could not be obtained. A soldering iron was finally used to seal the joint. This problem can be avoided by purchasing the drum fitted with the correct socket[10].

Gas drums made of HDPE could probably be supplied by the manufacturers of the water tanks made of this material. As these tanks are distributed in the rural areas of South Africa, the gas drums could also be made available in rural areas. However, it is unlikely that the

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[10]According to Dr T B Scheffler of the University of Pretoria a mechanical joint with a rubber washer or an O-ring seal could also be used at the gas outlet. (Personal communication with Dr Scheffler in August 1994.)

gas drums would be distributed in remote rural areas. Fortunately these drums can be transported with little difficulties because of their relatively low weight.

4.2.9 Guide systems for the gas drum

The biogas plant built at the homestead of the Mathabela family is fitted with an internal guide system for the gas drum. This comprises a galvanised iron central pole that is fixed into the floor slab and the baffle wall, as well as a galvanised iron guide pipe that is fitted at the centre of the gas drum. The latter fits over the central guide pole, allowing the gas drum to move up and down without tilting or scratching against the sides of the digester (see Figure C.1 in Appendix C).

This design was considered to be somewhat expensive as the central guide pole of galvanised iron had to be fairly long (almost 4 m in the case of the Mathabela family plant). It was therefore decided to install an external guide system at the experimental plant that was built at the UP. This consisted of a metal ring that was suspended above the gas drum from three points, and the galvanised iron pipe that was fitted onto the asbestos cement drum and also served as the gas outlet. The latter fitted through the metal ring, allowing the drum to move up and down without tilting (see Figure C.5 in Appendix C). Although this system functioned well, it did not provide any substantial benefits compared to the internal guide system, while it was more cumbersome to install.

When the HDPE drum was installed on the experimental plant, this guide system was at first retained. A rigid PVC pipe was fitted to the top of the HDPE drum to serve as the gas outlet and to guide the drum by sliding up and down inside the suspended metal ring. However, this system did not function well due to the flexibility of the drum roof. The drum was prone to tilting, particularly when weights were placed onto the drum to increase the gas pressure.

The suspended metal ring was therefore removed, and four small wheels were mounted on top of the digester wall to guide the drum. However, this did not provide for the adequate guiding of the drum when it reached its highest position. This problem was compounded by the tendency of the drum to deform under the pressure of the wheels. These problems were addressed by providing the drum with the metal framework described in Section 4.2.8, and by providing a second set of guiding wheels above the first set (see Figure C.6 in Appendix C). The gas drum is therefore guided by the movement of the wheels along the steel channels fixed to the drum. This guide system has functioned very well, its main drawback being that the drum cannot be rotated to break the scum which forms on top of the slurry, as is possible in the case of the other guide systems described above.

4.2.10 Slurry inlet and outlet arrangements

The biogas plant at the Mathabela family's homestead was provided with both an inlet and an outlet pipe and at no stage did this system provide any difficulties. When the experimental plant at the University of Pretoria was designed, it was decided to test the use of an overflow as outlet for the digester. This is the arrangement commonly used in India in the case of plants smaller than approximately 10 m^3 (United Nations 1980: 110). This was seen as a measure to simplify the design and reduce the costs of the plant slightly.

However, this arrangement was found to be unsatisfactory, as solids tended to collect and dry out in the overflow, thereby blocking the flow of slurry from the digester. Moreover, the plant at the UP seems more prone to internal blockages, as the gas drum can obstruct the flow of the slurry to the overflow. According to Werner *et al* (1989: 50) the digestion efficiency of a plant with an overflow is approximately 20 % less than one fitted with an outlet pipe.

4.3 The fixed-dome biogas plant

The fixed-dome plant comprises a closed tank that contains both the digesting slurry and the gas which is produced (see Figure 4.3). The gas storage area in the top of the digester has a dome-shape, as such a structure can be built at relatively low cost to be of sufficient strength to withstand the gas pressures inside a fixed-dome digester without the formation of cracks (Sasse 1988: 31). Generally the fixed-dome digester is built either in a hemispherical shape or in the shape of a cylinder with a dome-shaped roof. Digester sizes generally do not exceed 20 m^3 (Werner *et al* 1989: 62).

Any type of organic waste material can be utilised in a fixed-dome plant, including fibrous material such as crop residues, and human excreta. The plant is often operated in a semi-batch mode, e.g. in China. In such cases the digester is filled with plant matter (e.g. straw) and animal manure at the onset, after which animal manure and/or human waste is added on a regular basis (Fulford 1988: 38). However, it can be operated on a semi-continuous basis as in the case of the floating-drum plant.

In fixed-dome plants gas storage is provided by means of the displacement of slurry from the digester. As the quantity of gas in the upper part of the digester increases, the gas pressure also increases. This results in the displacement of slurry from the digester into the displacement tank which is connected to the outlet pipe. If the gas is utilised, the slurry in the displacement tank returns to the digester. The gas pressure corresponds to the difference between the slurry level in the digester and that in the displacement tank and therefore varies with the quantity of gas stored. Fixed-dome plants are generally designed to provide for a maximum gas pressure of 1 m water gauge. Because of the variation in gas pressure, gas appliances may need to be adjusted during use.

The operation and utilisation of the fixed-dome plant is therefore more complex than that of the floating-drum plant. Blockages in the plant are less evident, as the volume of slurry which enters the displacement tank when fresh slurry is added to the digester, is not clearly visible. In addition, the quantity of gas which is stored in the digester is not visible as in the case of the floating-drum plant. It would therefore be necessary in general to train users more extensively with regard to the operation and utilisation of the fixed-dome plant. Werner *et al* (1989: 56) recommends the implementation of fixed-dome plants under the following conditions only:

- if users are sufficiently familiar with the operation of such plants, and
- if experienced biogas technicians are available to build the plants.

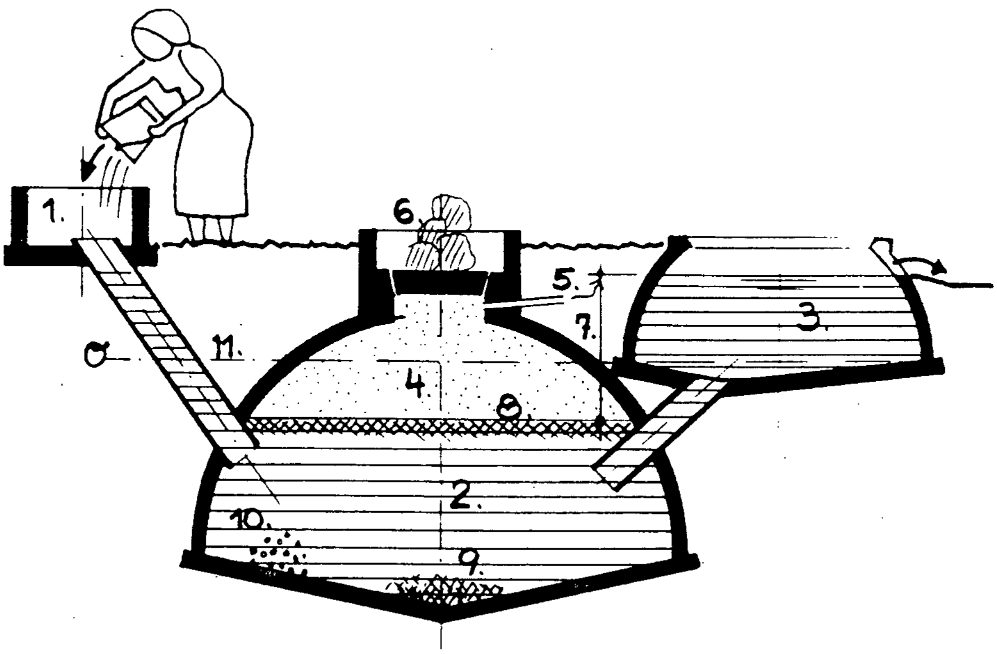

Figure 4.3: A fixed-dome biogas plant. (Sasse 1988: 15)

The second point highlights an important concern regarding the fixed-dome plant, namely the difficulty to build it successfully, i.e. without irreparable cracks forming in the dome which result in gas leaks (Werner *et al* 1989: 56). The decision to focus on the floating-drum plant rather than the fixed-dome plant, which was made in the early stages of this study, was greatly influenced by this concern, particularly as the project funded by the Department of Mineral and Energy Affairs placed considerable emphasis on the demonstration of biogas technology to potential users. As mentioned in Section 4.2, the experience of the RIIC in Botswana was noted in particular. The RIIC had sent a builder to China for training in the construction of fixed-dome plants, but was unable to build a digester which did not develop leaks[11].

According to Werner *et al* (1989: 62) the main advantages of the fixed-dome plant are its low initial cost and its long lifetime if properly constructed. The plant comprises no moving

[11]Personal communication with Mr Richard Tsitloe of the RIIC.

parts which are prone to wear or breakage, and no major metal components which are prone to corrosion. Fixed-dome plants also require relatively little maintenance if they are properly constructed. In addition, the digester is well-insulated compared to the floating-drum plant, as it is completely buried. As mentioned above, the fixed-dome plant also allows the utilisation of a wide variety of feed materials.

The fixed-dome plant seems to have gained popularity as a suitable option for small-scale applications of biogas technology in underdeveloped countries. For example, it is increasingly being used in India (Kijne 1984: A24) where the floating-drum plant was originally developed, and it is the preferred design in Tanzania (Kellner and Lwakabamba 1985: 316). For this reason more attention was given to the fixed-dome plant in the latter part of this study, which included the construction of a prototype on a dairy to the south of Pretoria (see Section 8.6). In the discussion that follows some aspects of the design and construction of fixed-dome biogas plants will be considered. Design drawings of the prototype built as part of this study are provided in Appendix B.

4.3.1 The brick fixed-dome plant

A variety of materials have been used for the construction of fixed-dome plants, particularly in China (Van Buren 1979), but bricks are most commonly used for this purpose in countries such as India and Tanzania (Kijne 1984: A24).

A particular design of the brick fixed-dome plant is promoted by the German Appropriate Technology Exchange (GATE) in countries like Tanzania (Sasse, Kellner and Kimaro 1991: 22). Detailed information is available on this design and the construction technique used, as well as the requirements for successful construction. According to Kellner and Lwakabamba (1985: 316) the successful construction of fixed-dome plants from bricks requires both highly skilled and well-trained masons, as special building techniques are required, and proper supervision of the construction process, as the workmanship must follow precise specifications. The gas storage space in particular has to be well-built to prevent the formation of cracks, often as a result of the relatively high gas pressure which develops in a fixed-dome plant. In addition, the quality of the bricks utilised for construction is of the utmost importance (Roeske 1987: 131). For these reasons the construction of a brick fixed-dome digester as part of this study was not regarded as feasible, as the project funded by the DMEA did not allow for the development of the skills required to build a brick dome successfully.

Shortly before the completion of this study, it came to the attention of the author that a fixed-dome biogas plant built of bricks exists at the Ananda Marga Mission in Orange Farm, south of Johannesburg. From discussions with a religious leader at the mission, it was established that the dome had been built by laying bricks onto a mould of wood and soil and covering it with mortar. However, details on the construction technique could not be obtained. The technique used for the construction of this plant appears to be similar to one described in the Guidebook on Biogas Development (United Nations 1980: 43). It differs substantially from the one which is promoted by GATE. Unfortunately insufficient information is available on this design of the fixed-dome plant and the technique used for construction to enable its evaluation in terms of its reliability and the level of skills required for construction.

4.3.2 The ferrocement fixed-dome plant

The experience gained in the construction of ferrocement biogas digesters during the project funded by the DMEA, both at the Mathabela homestead (see Section 8.2) and the piggery east of Pretoria (see Section 8.5), confirmed that ferrocement was particularly suitable for this purpose (see Section 4.5). Thus the possibility of building a fixed-dome digester of ferrocement was conceived, and the CSIR subsequently funded the construction of such a plant at a small dairy south of Pretoria (see Section 8.6). The completed digester is shown in Figure C.11 in Appendix C.

The ferrocement digester has a hemispherical shape, as this provided the easiest way in which to build a digester with a dome-shaped roof using ferrocement. The digester was constructed by erecting a self-supporting framework which comprised reinforcing rods tied together in the form of a grid, onto a reinforced concrete floor. A layer of chicken wire was attached to the inside as well as the outside of the framework. The first layer of plaster was applied simultaneously from the inside and the outside, after which two additional layers were applied, one on each side of the first layer.

The ferrocement fixed-dome plant would probably be more expensive than a similar plant built of bricks, because of the relatively large quantity of reinforcement employed in the digester. However, as the ferrocement digester has been designed with consideration of the expected maximum loads, e.g. the maximum gas pressure that could develop inside the digester, the risk that cracks may develop in the dome has been reduced significantly.

4.4 The flexible cover biogas plant

The flexible cover biogas plant (illustrated in Figure 4.4) comprises a trench-like digester which is covered with a plastic or rubber "balloon" that serves as a gas holder. The digester can be built of bricks or ferrocement, while the gas holder can be made of a variety of materials including PVC, polyethylene and butyl rubber (Werner *et al* 1989: 74). The design is particularly suitable for large-scale biogas plants, and digesters of up to 540 m^3 in size have been built using this design (Fulford 1988: 57).

The plant is mainly suitable for the digestion of animal manure (Werner *et al* 1989: 63), and its operation is similar to the floating-drum plant (see Section 4.2). An important difference between these two plants relates to the shape of the digesters. While both the floating-drum plant and the fixed-dome plant are generally operated as partly mixed digesters, the longitudinal shape of the digester in the case of the flexible cover plant provides for a limited degree of mixing only, so that plug-flow digestion tends to occur (see Section 3.2.2). It is also difficult to insulate the flexible cover biogas plant well, because of the large surface area of the digester which would generally be exposed to ambient temperatures.

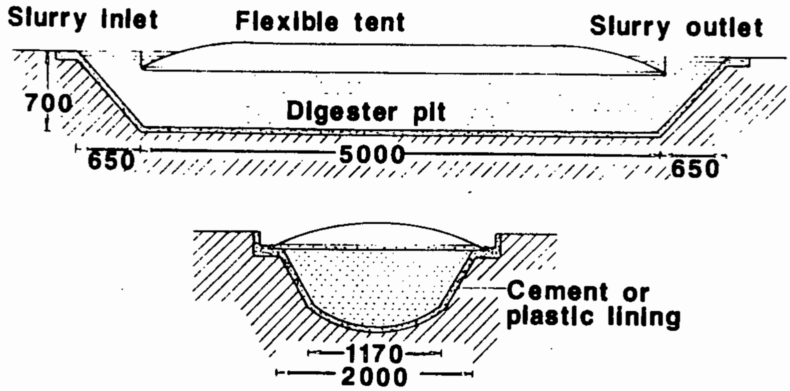

Figure 4.4: A flexible cover biogas plant. (Fulford 1988: 52)

The gas pressure in the flexible cover plant is generally low, i.e. only a few centimetres of water pressure (Fulford 1988: 54). The pressure can be increased by placing weights on the gas holder, as was done in the case of the pilot-plant that was built as part of this study (see Section 8.5.3). However, this would not be possible in the case of a large-scale biogas plant of this design. Then it would be best if the gas was used in an engine, as it would be drawn into the carburettor by suction, and very little gas pressure would therefore be required. The gas pressure increases when the gas holder is full as the gas holder material usually does not allow much expansion. Because of the large upper surface area of the digester in relation to its volume, a significant quantity of slurry can be displaced from the plant when the gas pressure increases. The design of the plant therefore needs to make provision for the storage of the slurry which is displaced when the gas pressure increases. This can be done by providing for an increase in the level of the slurry in the digester outside of the gas holder to accommodate the slurry which is displaced from within the gas holder. The inlet and outlet pipes also need to be long enough to ensure that the slurry does not leave the plant if the level of the slurry raises as a result of the increase in gas pressure (Fulford 1988: 54).

It has been found that the flexible cover biogas plant presented the least expensive option for biogas production in countries where locally manufactured materials have been available for the gas holder (Fulford 1988: 53). As discussed in Section 4.6, this design provides for the production of biogas at a lower cost than the other designs considered during this study. However, the lifetime of the gas holder could be fairly short if it is subjected to mechanical damage. This plant would therefore not be suitable for implementation at sites where access to the plant cannot be controlled, and where carelessness or vandalism might be a problem. Because of the greater risk of damage, it has not been considered for application in the rural areas of the former homelands.

A small pilot-plant of the flexible cover design was built at a commercial piggery as part of this study (see Section 8.5). The plant is shown in Figure C.9 in Appendix C, and design drawings are provided in Appendix B. The digester was built by lining the sides and the bottom of a trapezoidal trench with ferrocement. The first layer of plaster was applied directly onto the soil as a "blinding layer", to which a double layer of chicken wire was attached. The chicken wire reinforcement was then covered with layers of a strong plaster mix. Stainless steel hooks were fitted into the digester walls to act as anchors for the gas holder.

The gas holder was made on-site, using inexpensive plastic sheeting and PVC adhesive tape. Holes were made in the seam of the gas holder and these were reinforced with brass grommets. A nylon rope was inserted through the holes and the gas holder was attached to the steel anchors by means of the rope. The gas outlet comprised a PVC socket attached to two PVC disks which were glued and bolted to the gas holder. When this gas holder developed punctures, it was replaced with a factory-made gas holder which had been specially designed for this purpose (see Figure C.10 in Appendix C). This gas holder is made of 0.5 mm thick PVC Elvaloy which is UV-stabilised as well as being fairly resistant to mechanical damage, and is guaranteed for a period of ten years. In general a gas holder which is made of material containing PVC is preferred because of the ease with which it can be repaired on site, using special glues.

4.5 Use of ferrocement for digester construction

As discussed above, ferrocement was used successfully for the construction of three of the digesters that were built as part of this study. Ferrocement is a building technique which comprises the plastering of a cement-rich mortar onto a mesh of wire reinforcement, generally including chicken wire. The suitability of ferrocement for digester construction can be attributed to the same characteristics which have made it suitable for water tank construction, particularly in underdeveloped rural areas, as discussed by Watt (1978: 11):

- Ferrocement is often less expensive than alternative materials, particularly as the tank walls are relatively thin (i.e. 3-10 cm, depending on the size of the tank) (*ibid*). However, this would also depend on the quantity of reinforcement used (e.g. the ferrocement fixed-dome plant required a relatively large quantity of reinforcement).

- Ferrocement is corrosion resistant, and the expected lifetime of a ferrocement water tank is in excess of 50 years (*ibid*).

- The thin walls of the tank, together with the dense wire reinforcement, enable it to handle loads without cracking. Even if cracks appeared under moderate loading, these would not be wide enough to allow water to reach the reinforcing wires and thereby to start corrosion (Watt 1978: 27). Moreover, hairline cracks which formed in a digester wall would generally be sealed by the slurry.

- The basic materials required for ferrocement construction, such as water, sand, cement and wire, are generally available in rural areas.

- The skills required, such as plastering skills, are often available in rural areas, while untrained people would be able to build satisfactory water tanks after only a few days' supervision (Watt 1978: 12). In addition, a considerable proportion of the construction work on a tank can be done by unskilled workers. This would allow for the reduction of costs by involving the owners of a biogas plant in its construction.

- The construction techniques involved are simple and do not require sophisticated equipment or a power supply, with the result that trained supervision can be kept to a minimum. Leaks resulting from bad workmanship can be repaired easily, while very little maintenance is generally required after construction.

The versatility of ferrocement has also proven to be valuable for the purposes of digester construction. As discussed in this chapter, three different ferrocement techniques were used during this study to build the three digesters: The cylindrical digester was built using a mould, while the hemispherical digester required the erection of a self-supporting framework of reinforcement, and the trapezoidal digester was constructed against the sides of the hole. The suitability of each of these techniques would depend on the particular circumstances. For example, although a mould requires an initial investment, it has advantages over the other techniques if a number of plants are to be constructed, as it requires less reinforcement than a self-supporting framework and it is independent of the type of soil in an area. However, as the use of moulds with complex shapes are difficult and expensive (Watt 1978: 28), it is only feasible to build a cylindrical digester using this technique.

4.6 Cost analysis of biogas plants

A cost analysis has been conducted for each of the four biogas plants discussed in this chapter, which have been developed during this study. This was done for the purposes of comparing the costs of the different designs, and to assess the energy costs of the biogas which can be produced in these plants (see Section 5.4 for a comparison between the costs of biogas and other fuels). The following procedure was employed:

1. The basic installation costs of each plant were determined, including the cost of the materials for the plant and the gas pipeline, and the labour cost for the digging of the hole for the digester, the construction of the plant, the filling of the digester with slurry, and the installation of the gas pipeline. This information is presented in Appendix H.

   The costs of the floating-drum plant comprising a tapered brick digester and a HDPE gas drum were calculated for the final design after all the changes had been made to the gas drum and the guiding system (see Section 4.2.8), while the costs of the flexible cover design also reflect the final design with the improved gas holder (see Section 4.4). The costs of the floating-drum plant comprising a ferrocement digester and a mild steel gas drum, were calculated for a larger digester volume of 10 m^3, built according to an improved design. The changes which have been made mainly involve the reduction in the size of the gas drum relative to the digester size, as it had been oversized before, and the installation of a ferrocement gas deflecting ledge. The costs of the fixed-dome plant were calculated for the plant as installed. In each case provision was made for the installation of a gas pipeline of approximately 30 m length, with the necessary accessories.

The costs of materials reflect the prices that were paid in Pretoria during 1992. In order to calculate the labour costs, the following wage rates were assumed, based on the wages that were paid in rural areas in 1992[12]:

- R 15/day for unskilled labour
- R 30/day for skilled labour, e.g. brick laying and plastering
- R 50/day for skilled technical work, e.g. welding

Transport costs and the costs of supervising the construction process were not considered, as these may vary considerably depending on the circumstances.

2. The actual installation costs of each biogas plant were estimated for urban and rural areas respectively, based on the following assumptions:

   - Wage rates paid in urban areas are double those paid in rural areas.
   - Material costs in rural areas are 15 % higher than in urban areas.

3. The maintenance costs were estimated by assuming that the annual expenditure on maintenance constituted a small percentage of the construction costs of a plant, i.e. the installation costs, excluding the costs of digging the hole for the digester and the costs of filling the plant with slurry. Because of the different maintenance requirements of the plants, different percentages were used in each case:

   - 2 % for the fixed-dome plant
   - 3 % for the flexible cover plant
   - 4 % for the brick digester with the HDPE drum
   - 7 % for the ferrocement digester with the mild steel drum

   The maintenance costs of the latter are particularly high as the gas drum has to be repainted annually to ensure a long lifetime. No provision was made for the replacement of any of the gas drums or the flexible gas holder, as the lifespan of each of these components was expected to be in excess of the period over which the cost analysis was conducted (i.e. ten years). Operational costs were not considered either, as this would differ under different circumstances, and the realistic costing of the time spent by family members on the operation of a household plant, would be extremely difficult.

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[12]Personal communication with Dave Still, an engineer employed by the Division of Water Technology (CSIR) at the time.

4. The present value (in 1992 rand) of the various expenditures on maintenance that would be incurred over a period of ten years was calculated in each case at discount rates[13] of 0-5 %.

5. The total present value of each biogas plant, including the installation costs and the maintenance costs during this period, was calculated, and this amount was amortised over the same period, at corresponding discount rates. Although the lifespan of a biogas plant is likely to be 20 years or more, a period of ten years was used in this analysis, as this is seen as the maximum pay-back period that would be acceptable to farmers or families who install biogas plants (Werner *et al* 1989: 112).

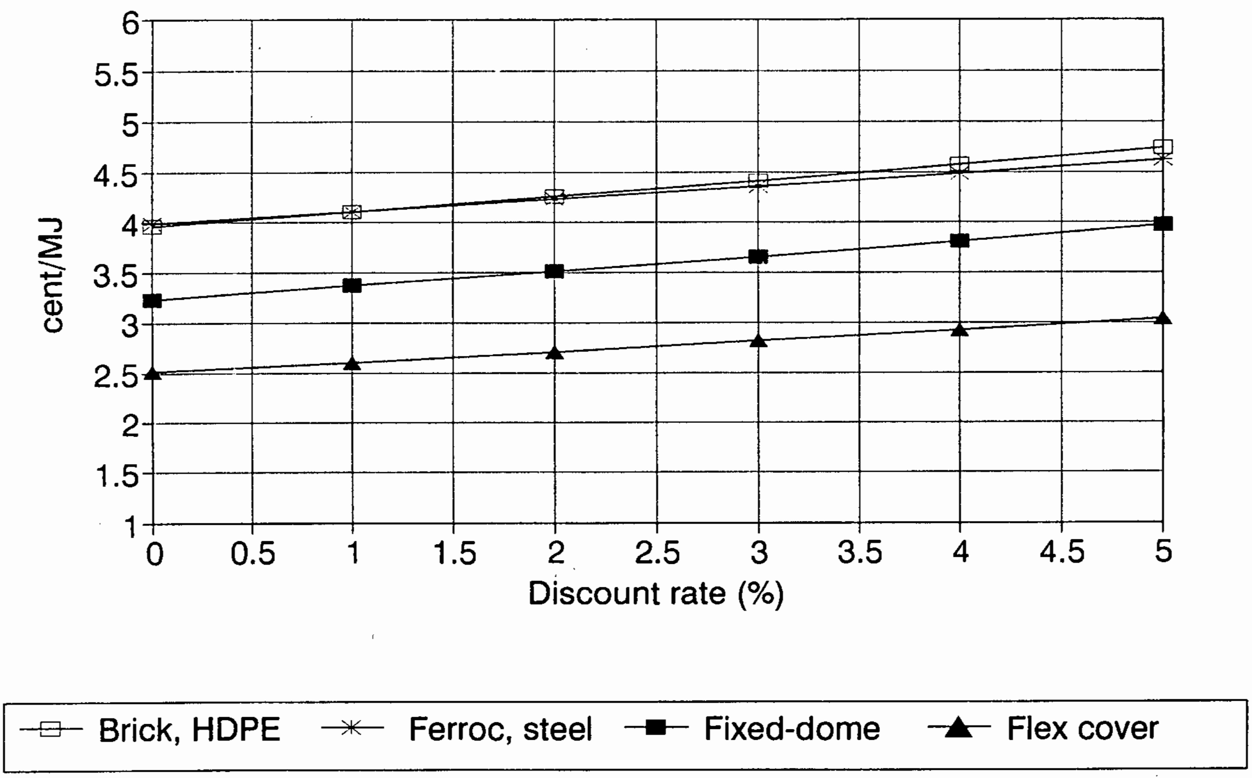

Figure 4.5: Calculated energy costs (1992 rand) of biogas for four different plant designs constructed in rural areas.

[13]The discount rate constitutes the difference between the inflation rate and the interest rate at which money can be invested. As this can differ considerably depending on the manner in which a biogas plant is financed, a range of discount rates has been considered in this analysis.

In order to compare the costs of the different biogas digesters, and to obtain an estimate of the energy costs of biogas, it was assumed that all the biogas plants would achieve the same volumetric gas production rate, i.e. a mean annual volumetric gas production rate of 0.25 m^3 of gas per cubic metre of digester volume per day. This appears to be a realistic rate for biogas plants installed in temperate climatic zones (Theilen 1990: 17). The calorific value of the gas was assumed to be 21 MJ/m^3 (5.96 kWh/m^3) (Sasse 1988: 55). The energy costs of the biogas that would be produced in the various plants under these conditions, are presented in Figures 4.5 and 4.6 for rural and urban areas respectively.

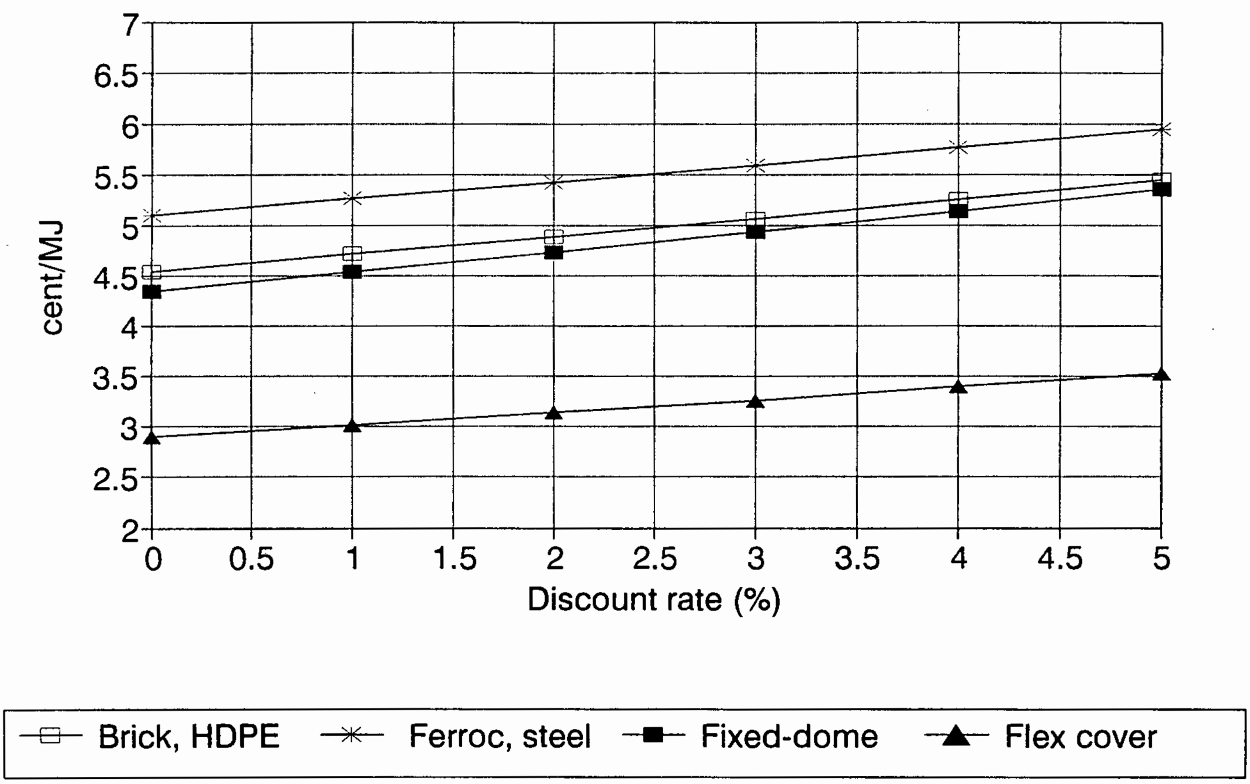

Figure 4.6: Calculated energy costs (1992 rand) of biogas for four different plant designs built close to urban areas.

From this it would appear that the costs of the flexible cover plant are significantly lower than the other plants, particularly if installed close to an urban area. The fixed-dome plant seems to be the least-cost option for small-scale plants, particularly in rural areas, while the cost of the brick digester with the HDPE gas drum is comparable to that of the fixed-dome plant in urban areas. The ferrocement digester with the mild steel gas drum appears to be the most costly option in urban areas, while the two floating-drum plants are of comparable (high) cost in rural areas. The costs of the plants are all higher when built in urban areas compared to rural areas. The fixed-dome plant and the ferrocement digester with the mild steel gas drum show the highest increases, probably as the construction of these plants are more labour-intensive than the other two.

The costs of the ferrocement digester with the mild steel gas drum would probably be even higher compared to the other plants if the analysis was conducted over a longer period, as the mild steel gas drum would require replacement after approximately ten years (Werner *et al* 1989: 62). The HDPE drum and the PVC Elvaloy gas holder are both expected to have a lifespan in excess of ten years, while no expense of comparable magnitude should be incurred during the lifetime of the fixed-dome plant. The relatively high costs of the brick digester with the HDPE gas drum can be attributed mainly to the thickness of the tapered digester walls, which are three times as thick as the ferrocement walls of the other three digesters. A floating-drum plant comprising a ferrocement digester and a HDPE gas drum rather than a mild steel drum, is expected to be less costly than either of the floating-drum plants considered here, particularly in rural areas, as it would eliminate the two most costly elements of these digesters, i.e. the mild steel drum and the tapered brick digester.

4.7 Conclusions

The advantages of the floating-drum plant are such that this design would be an attractive option in many instances. Its main drawback has been the costs associated with the maintenance and replacement of the mild steel gas drum. However, an HDPE gas drum may provide a suitable alternative, as it appears to satisfy most of the requirements for a gas drum such as low maintenance and a relatively long lifespan.

Based on cost considerations it would appear that the most suitable floating-drum design for digester sizes of 10 m^3 and less, would be the ferrocement digester with the HDPE gas drum. Larger plants would have to be provided with a tapered brick digester, because of the restrictions on the size of the ferrocement digester. This digester could also be built where a high water-table or a shallow rock layer prevents the excavation of a deep hole, or if the mould required for the construction of the ferrocement digester is unavailable. An attractive feature of the tapered digester is the fact that it provides some flexibility with regard to the diameter of the gas drum required for a particular digester size.

A floating-drum plant fitted with an outlet pipe rather than an overflow, and an internal rather than an external guide system, is generally preferred. The water-jacket version of the tapered digester could be used for the digestion of human waste and fibrous materials, in which case an HDPE drum fitted with an external guide would have to be used.

The fixed-dome plant has a number of important advantages. It has no moving parts which are prone to wear or breakage, and comprises no major metal components which are prone to corrosion. Fixed-dome plants also require relatively little maintenance if they are properly constructed. In addition, the digester is well-insulated compared to the floating-drum plant, as it is completely buried, and the fixed-dome plant also allows the utilisation of a wide variety of feed materials.

In other countries the main advantage of the fixed-dome biogas plant has been its low cost when constructed of bricks. However, the high level of skills required for the successful construction of a brick dome would severely limit its implementation in South Africa, as these skills are not generally available in the country. The ferrocement fixed-dome design seems to be a viable alternative to the brick design, as the risk of plant failure has been reduced considerably, and most of the skills required are available in rural areas. The costs of this plant in rural areas were found to be considerably lower than either of the floating-drum plants built during this study. In the longer-term this plant would compare even more favourably with the floating-drum plants, because of the absence of a large component which would need replacement, such as the gas drum.

The flexible cover plant developed in this study was relatively simple to construct, and the costs of this plant were found to be significantly lower than the other plants considered here. Both of these considerations are particularly important in the case of large-scale biogas plants. In addition, the PVC Elvaloy used for the gas holder appears to be well-suited for this purpose. This plant therefore seems to have considerable potential for large-scale applications. However, additional research would be required to develop a large-scale plant of this design which could be implemented in South Africa.

CHAPTER 5
USE OF BIOGAS AS ENERGY SOURCE

5.1 Introduction

In this chapter some technical and economic considerations regarding the use of biogas as energy source will be considered shortly. The feasibility of using biogas as a fuel would generally depend on the energy applications involved and the suitability of biogas for these purposes, the quantity of gas that would be required to provide these services, and the cost and convenience of alternative fuels which can be used to meet such needs. Some of the properties of methane and biogas which are relevant to this discussion, are presented in Table 5.1. An attempt will also be made to estimate the quantity of biogas that would be required by rural households who use the gas for domestic purposes. Some socio-economic aspects of the use of biogas by people in underdeveloped areas will be discussed in Section 9.2.

Table 5.1: Properties of methane and biogas.

Property	Methane	Biogas
Calorific value at standard temperature and pressure (MJ/m^3)	37.7	22.6*
Air/gas ratio required for combustion (m^3/m^3)	9.5	5.7*
Relative density (air = 1)	0.554	0.940*
Combustion speed (cm/s)	43	40*
Flammability limits by volume (percentage of gas in air)	5-15	6-25
Octane rating	130	-
Ignition temperature (°C)	650	700

* methane:carbon dioxide = 60:40

5.2 Uses of biogas

The most common use of biogas is in stoves or burners. A number of stoves which have been specially developed for biogas are available from countries like India and Brazil (Werner *et al* 1989: 79). Based on the evaluation of burners by Werner *et al* (1989: 79), it would appear that the Jackwal biogas burner which is manufactured in Brazil is one of the best ones available.

During this study locally available low-pressure gas burners made of cast-iron (see Figure C.8 in Appendix C) were adapted for use with biogas. Tests were conducted on burners of three different sizes to determine the size of the jet required in each case to ensure the satisfactory performance of the burner. The following jet sizes were found to be best at a gas pressure of 75 mm water pressure:

- 8 cm diameter ring burner: jet size of 1.5 mm
- 11 cm diameter ring burner: jet size of 2-2.5 mm
- stove comprising two concentric ring burners with diameters of 9 cm and 18 cm: jet sizes of 1.5 and 2.5 mm respectively

At smaller jet sizes the burners did not operate at all, while larger jet sizes resulted in very low burner efficiencies. Werner *et al* (1989: 78) predicted that adapted burners would be less efficient than specially designed biogas burners. The efficiencies of the burners that were tested during this study, were determined by means of a standard water boiling test. The measured efficiencies ranged from 37 % for the smallest burner, and 33 % for the medium burner, to 26 % in the case of the stove with two burners. These efficiencies seem extremely low when compared to those reported for biogas burners, e.g. 55 % (Sasse 1988: 55). However, this discrepancy could result to some extent from the use of different methods for determining the efficiencies of burners.

Biogas lamps are considered here very shortly, as no lamps were used during this study. According to Werner *et al* (1989: 81) the maximum light output which can be achieved with a biogas lamp is comparable to that of a 75 W electric light bulb. However, the efficiency of a biogas lamp appears to be significantly lower than an electric bulb (Sasse 1988: 55). Werner *et al* (1989: 82) point out that many commercially available biogas lamps provide poor lighting at high gas consumption rates, as they have not been optimally designed for the low or fluctuating pressures typical of biogas utilisation. The Patel Outdoor single lamp manufactured in India seems to be one of the best lamps available (*ibid*).

Biogas can be also be used for a variety of agricultural applications, such as the heating of animal houses, and running engines for different purposes. Industrial boilers which are used to heat water for the purpose of heating chicken houses indirectly, and which can be operated on biogas, are available from a company in Johannesburg (Hamworthy Engineering Africa). In addition, both four-stroke diesel and spark-ignition engines can be modified to run on biogas (Werner *et al* 1989: 86).

5.3 Calculation of biogas requirements

The biogas required by a household or farmer can be estimated in different ways. Two simple methods will be discussed here, which will be used to calculate the biogas requirements of rural households who may adopt biogas technology. Ideally the results obtained using the two methods should be compared to arrive at a final estimate of the quantity of biogas required.

5.3.1 Calculations using equivalent energy values of fuels

The quantity of biogas which is equivalent in energy value to the fuels which will be replaced by the biogas can be determined, by considering the energy value of the different fuels as well as the efficiency of the appliances involved. In Table 5.2 calculated quantities of commonly used fuels as well as electricity, which are equivalent to 1 m^3 of biogas at 20 °C and 1 atmospheric pressure are presented. Unfortunately similar efficiencies for paraffin and LPG lamps are not available[14], and these could therefore not be included in the table.

An attempt was made to estimate the quantity of biogas that would be required by households in rural areas who adopt the technology, by considering the current energy consumption patterns of a relatively affluent rural household in a former homeland area. This was done as it is more likely that biogas will be utilised by some of the better-off smallholders in these areas. The consumption patterns related to biogas were expected to be somewhat similar to those related to fuels like paraffin and LPG, and the latter in particular is more commonly used by the more affluent households in the former homelands.

In Table 5.3 information on the energy use of the Mogope family in the village of Welverdiend in Gazankulu, who was interviewed in October 1992, is presented (see Section 9.5 for discussion on family). The family used fuelwood to cook on an open fire, while gas was used mainly for refrigeration. Paraffin was used mainly for lighting, while a small quantity was also used for cooking. The family reportedly used one bakkie-load of fuelwood every one to two months. This was converted to an equivalent mass of fuelwood by assuming that a bakkie-load of fuelwood constituted about 650 kg of wood, as reported by Griffin, Banks, Mavrandonis *et al* (1992: 10). The mean household energy consumption in Welverdiend, as well as the average consumption by households using particular fuels, which have been reported by Griffin *et al* (1992), are also presented in Table 5.3 for comparative purposes. The quantities of biogas which are more or less equivalent to the quantities of fuels consumed by the Mogope family are given in the final column in the table. The quantity of biogas required for refrigeration was determined by assuming that the efficiency of a biogas fridge was 66 % of the efficiency of an LPG fridge.

It therefore appears that the Mogope family would require more than 2.5 m^3 of biogas per day just to satisfy their cooking needs. In addition, an estimated 2.3 m^3 of biogas would be required on a daily basis if a biogas fridge was used. The quantity of biogas that would be required for lighting purposes could not be calculated, as no figures are available for the efficiency of paraffin lamps, as mentioned above.

[14]Personal communication with Dr Uken of the Cape Town Technikon.

Table 5.2: Quantities of fuels equivalent to one cubic metre of biogas.

Fuel/energy form	Energy content (MJ/unit)	Application efficiency (%)		Net energy content (MJ/unit)	Quantity equivalent to 1 m^3 of biogas
dry dung	12 MJ/kg	cooking	12	1.4 MJ/kg	8.3 kg
fuelwood	17 MJ/kg	cooking	12	2.0 MJ/kg	5.8 kg
coal	27 MJ/kg	cooking (fire) cooking (stove)	12 25	3.2 MJ/kg 6.8 MJ/kg	3.6 kg 1.7 kg
paraffin	37 MJ/ℓ	cooking	50	18.5 MJ/ℓ	0.63 ℓ
LPG	49.8 MJ/kg	cooking	70	34.9 MJ/kg	0.33 kg
electricity	3.6 MJ/kWh	cooking lighting	80 9	2.9 MJ/kWh 0.3 MJ/kWh	4 kWh 2 kWh
petrol	31 MJ/ℓ	engine	25	7.8 MJ/ℓ	0.6 ℓ
diesel	42 MJ/ℓ	engine	30	12.6 MJ/ℓ	0.4 ℓ
biogas	21 MJ/m^3	cooking lighting engine	55 3 24	11.6 MJ/m^3 0.6 MJ/m^3 5.0 MJ/m^3	1 m^3 1 m^3 1 m^3

Sources: Griffin *et al* (1992: 9); National Academy of Sciences (1977: 45); and Sasse (1988: 55).

Table 5.3: Quantities of biogas equivalent to the energy consumed by the Mogope family in Welverdiend. The mean household fuel consumption in the village and the average consumption by households using particular fuels are provided for comparative purposes.

	Welverdiend (mean for total sample)	Welverdiend (mean for users of fuel)	Mogope family	Quantity of biogas equivalent to consumption of Mogope family
Size of household	8.4		6	
Monthly household income	R 384		> R 1 500	
Number of cattle owned				
Monthly paraffin use (ℓ)	14	15	30	
Monthly gas use (kg)	1.2	11	19	68 m^3/month (2.3 m^3/day)
Monthly wood use (kg)	400	308 (collected) 858 (bought)	430	75 m^3/month (2.5 m^3/day)
Monthly coal use (kg)	4	45	0	
Monthly candle use (number)	15	21	little	
Monthly energy consumption (MJ)	7 848		9 434	

Source: Information on energy use in Welverdiend obtained from Griffin *et al* (1992).

5.3.2 Calculations based on duration of appliance use

The biogas consumption of a family or farmer can also be estimated by calculating the quantity of gas which is expected to be consumed by each appliance on a daily basis, using the gas consumption rates of the appliances as well as the estimated period for which each of the appliances will be used on a regular basis. This method therefore makes provision for energy needs which would only be met once a biogas plant has been installed.

Table 5.4: Gas consumption rates of appliances/engines.

Appliance/engine	Gas consumption rate (ℓ/h)
gas burners:	
household	150-500
industrial	1 000-3 000
5 cm diameter flame	330
10 cm diameter flame	470
15 cm diameter flame	640
locally available small burner	205
locally available medium burner	322-451
locally available large burner	575
gas stove:	
4 burners and oven	2 000 (max)
gas lamps:	
25-75 watt equivalent	100-180
60 watt equivalent	120-150
2 mantle lamp	140
3 mantle lamp	170
fridges:	
100 ℓ capacity	100-120
100 ℓ useful capacity	30-80
diesel-biogas internal combustion engine:	
per kW	500-800
4-stroke single-cycle, spark-ignition engine coupled with centrifugal pump with engine shaft output of 3 HP	2 620
spark-ignition engine:	
per kW	500-800
incubator:	
planar type	30-50
100 ℓ capacity	46-70
electrical generator:	
1 kWh generated with diesel-biogas engine	700

Sources: National Academy of Sciences (1977: 45); Sasse (1988: 55); Werner *et al* (1989: 79) and Renewable Energy Resources Information Center (1987: 3).

The biogas consumption rates of various appliances and engines are given in Table 5.4. The consumption rates which have been determined for locally available burners that were adapted for use with biogas, are also included. In addition, the quantities of biogas required to heat water can be estimated by using the following information which were presented by Sasse (1988: 55):

- 40 ℓ of biogas required to boil 1 ℓ of water
- 165 ℓ of biogas required to boil 5 ℓ of water

An attempt has been made to estimate the biogas requirements of the Mathabela family in Gazankulu, using information on the duration of different domestic chores that was obtained in October 1992. This information may not be very accurate, as the accounts of different family members did not always correspond. The following assumptions were made in order to calculate the quantity of gas required for the different purposes:

- A large household burner with a consumption rate of 500 ℓ/h is used to cook pap.
- For all other purposes a small household burner with a consumption rate of 250 ℓ/h is used.

The estimated biogas requirements of the Mathabela family which are shown in Table 5.5, appear to be somewhat lower than the estimated requirements of the Mogope family discussed in Section 5.3.1. However, this may result partly from financial constraints on the family which may prevent them from fulfilling all their energy needs. The energy use of the Mathabela family is discussed in great detail in Section 9.4.5.

Theilen (1990: 17) estimated the biogas requirements of a family of five which requires energy for the following purposes:

- cooking with 2 burners for 8 hours/day
- lighting by means of 4 bulbs for 4 hours/day
- running a 230 ℓ fridge for 24 hours/day

He found that such a family would require 2.4 m^3 of biogas for cooking only, and an additional 1.9 m^3 and 2.4 m^3 for lighting and refrigeration purposes respectively. This can be compared with the estimated gas requirements of an affluent family in a former homeland area that were discussed in Section 5.3.1. According to Sasse (1988: 55) a family of five consumes 0.85-2.5 m^3 of gas per day, depending on eating, bathing and other practices, while a family of ten people consumes 15-30 % more gas.

Table 5.5: Estimated biogas requirements of the Mathabela family for cooking and heating purposes (excluding space heating).

Purpose	Duration (min/day)	Biogas consumption (ℓ/day)
cooking a large quantity of pap once a day	90	750
cooking meat/gravy once a day	20	85
cooking breakfast once a week	5	20
boiling 1 ℓ of water for tea		40
boiling 2 ℓ of water five times a day for bathing boiling 5 ℓ of water twice a day for bathing		5 x 75 = 375 2 x 165 = 330
boiling 2 ℓ of water twice a day for dish washing		2 x 75 = 150
ironing of clothes	60	250
Total		2000

5.4 Availability and cost of other fuels

Experiences in other countries have shown that the utilisation of biogas technology for energy purposes is greatly dependent on the availability and costs of alternative fuels. In Thailand, for example, biogas technology had been adopted very slowly because of the availability of adequate supplies of other fuels (Fulford 1988: 1). In Brazil, on the other hand, the biogas programme benefitted from the high cost of imported fuels (*ibid*). In Tanzania the technology is only implemented if no real fuel alternatives are available to potential users (Sasse *et al* 1991: 13), as biogas plants have failed in the past because other fuels were easier to use (Kellner and Lwakabamba 1985: 315). Clearly it is not only the cost of biogas compared to other fuels which is of importance, but also the comparative convenience of the fuels (see Section 9.2.1 for a discussion of the impact of biogas technology on the work-load of households). However, particular attention will be given here to the costs of biogas compared to other fuels used for domestic purposes.

Generally a household biogas plant will only be financially viable if it provides for considerable savings on purchased fuels. According to Kellner and Lwakabamba (1985: 318) pay-back periods of 3-5 years have been achieved for household biogas plants in countries such as Tanzania, with consideration of the running costs and the interest on loan repayments. This has been possible mainly because of the high cost of commercial fuels which would be the alternatives to achieve the same standard of living (*ibid*).

In Section 4.6 the energy costs of biogas which is produced in the biogas plants developed during this study, were determined for a particular set of conditions, i.e. the costs of the biogas plants were analyzed over a period of ten years. In Table 5.6 the useful energy costs of biogas, which is produced in small-scale plants in rural areas, are compared with the costs of other energy sources used for cooking purposes in rural areas. The costs of fuels used for this purpose reflect the prices of domestic fuels in the five villages in the Mhala district of Gazankulu which were surveyed by Griffin *et al* (1992). Information from a very specific area was therefore used for comparative purposes, as no national data on the energy costs in rural areas were available. In addition, the prices reported by Griffin *et al* (1992) pertained to the same year as the base year used in the cost analysis of the biogas plants, i.e. 1992. The useful energy costs were calculated by using the energy content of fuels and the appliance efficiencies reported in Table 5.2.

The estimated costs of biogas therefore seem to compare favourably with fuels such as paraffin and LPG in the area, particularly in the case of the fixed-dome plant. On the other hand, energy sources such as coal and wood, and electricity in particular, could provide cooking at lower cost than biogas. However, this comparison between the fuels would not be generally valid, as the costs of energy sources, including biogas, are likely to differ considerably at different locations.

Table 5.6: Cost comparison between biogas and other energy sources.

Fuel	Cost per unit	Useful cost (c/MJ)
wood	7-26 c/kg	3.4-12.7
coal (fire) (stove)	23-43 c/kg	7.1-13.3 3.4-6.3
paraffin	138-156 c/ℓ	7.5-8.4
LPG	277-361 c/kg	7.9-10.4
electricity	9.7-16 c/kWh	3.4-5.6
biogas (fixed-dome plant)	68-83 c/m^3	5.8-7.2
biogas (floating-drum plants)	83-100 c/m^3	7.2-8.6

Sources: Costs of fuels other than biogas obtained from Griffin *et al* (1992).

5.5 Conclusions

The main use of biogas which have been considered in this study, is cooking and related activities. Locally available gas burners have been adapted successfully for use with biogas, although these burners appear to be less efficient than specially made biogas burners. The biogas requirements of a farmer or family can be estimated by considering the quantities of biogas which are equivalent to current fuel consumption, or by considering the duration of use and the gas consumption rates of appliances. The biogas requirements of two families in Gazankulu for cooking and related purposes were estimated as 2 m^3 and 2.5 m^3 per day respectively, which are similar to reported figures for other areas. The estimated useful costs of biogas in rural areas, which is produced in small-scale biogas plants, appear to compare favourably with the costs of paraffin and LPG in rural areas, particularly in the case of the fixed-dome plant.

CHAPTER 6

IMPLEMENTATION OF BIOGAS TECHNOLOGY ON FARMS AND SMALLHOLDINGS

6.1 Introduction

As discussed in Chapter 2, most of the potential users of biogas technology in South Africa are farmers and smallholders. In this chapter attention will be given to some practical considerations regarding the implementation of biogas technology on farms and smallholdings. Matters which are discussed include the quantities and properties of organic matter available which could be used for biogas production, the quantities of water required to operate biogas plants, the labour requirements of biogas plants, the possible benefits of implementing biogas technology on farms other than gas production etc. Throughout the discussion the focus will be mainly on the application of biogas technology on smallholdings in the former homelands. The information presented here should be useful to assess the suitability of a farm or smallholding for the application of biogas technology.

6.2 Utilisation of agricultural residues for biogas production

In order to implement biogas technology, sufficient quantities of substrate which is suitable for the generation of biogas are required. Some matters related to the utilisation of agricultural residues, and animal manure in particular, for biogas production are considered in this section. The manure yields of animals and the properties of fresh manure are first considered below, after which the quantities and characteristics of the manure which may actually be available for biogas production, are discussed. The properties of plant residues are summarised in Section 6.2.4.

The main focus of this study has been the utilisation of cattle manure for the production of biogas by smallholders in the former homelands. Cattle manure presents relatively little operational complexities when utilised in biogas plants (Werner *et al* 1989: 23), and are therefore highly suitable for this purpose. Pig manure is an excellent substrate for gas production, but is a more complex substrate than cattle manure, while the digestion of chicken manure appears to be fairly involved. The digestion of crop residues alone is very difficult, but a mixture of crop residues and manure can be digested successfully (Werner *et al* 1989: 26).

Considerable variation is found in the reported quantities and properties of the manure[15] produced by animals. The variation in these figures can be attributed to factors such as the following (Weller and Willetts 1977: 31):

- Characteristics of the animals, such as breed, age and live weight.
- External factors such as climate and diet, which also influence the water intake of animals.

Dietary aspects which influence the quantities and properties of the manure produced, include the quantity of feed consumed, its digestibility and the extent to which it is utilised by the animals (Werner *et al* 1989: 22). On average, 40-80 % of the organic content of feedstocks reappears as manure, while cattle excrete approximately one third of their fibrous fodder (*ibid*). Generally the animals on commercial farms would be well-fed both in terms of the quantity and quality of feeding compared to animals owned by farmers in underdeveloped areas. For example, cattle in the former homelands mostly depend on communal grazing lands for feeding, much of which is in a deteriorated state due to overgrazing (Bembridge 1990: 18). In the discussion that follows a distinction is therefore made, where applicable, between the manure produced by animals on commercial farms and those on farms and smallholdings in underdeveloped areas.

6.2.1 Manure yields

The quantity of manure which is produced at a particular location can be calculated on the basis of the live weight of the animals, as this generally provides a realistic estimate (Werner *et al* 1989: 22). The daily manure yields of cattle are summarised in Table 6.1. The yields for dairy and beef cattle refer to commercial farms, while the general figures mainly refer to cattle on smallholdings or farms in underdeveloped areas.

Table 6.1: Manure yields of cattle.

Quantity	Dairy cows	Beef cattle	General
Manure as % of live weight	7.2-12	4.1-8.8	9-10
Dung as % of live weight			5
Urine as % of live weight			4-5
Manure yield (kg/day)	36-45	28	
Dung yield (kg/day)			8-10

Sources: Fulford (1988: 35); Jewell *et al* (1981: 114); Funke, Knoesen and Venter (1984: 1); Hobson (1990: 98); Sasse (1988: 11); Weller and Willetts (1977: 31) and Werner *et al* (1989: 22).

[15]As used here, the term manure refers to both the dung and urine produced by animals.

As indicated in the table, a discrepancy exists between the typical manure yields from cattle on commercial farms and on farms in underdeveloped areas, although the manure yields as percentage of live weight are comparable. This could reflect a difference in the live weight of the animals in these two categories. According to Werner *et al* (1989: 22) the live weight of cattle varies between 135 and 800 kg. While a well-fed dairy cow or beef head may weigh 450 kg (Weller and Willetts 1977: 30), live weights in the range of 200-300 kg are used by Werner *et al* (1989: 22) for cattle in underdeveloped areas. Trace (1990: 65) observed that the cattle owned by the Mathabela family in Gazankulu (see Section 9.4) were generally fairly small, apparently as large cattle were either stolen, slaughtered or sold. Because of the poor conditions of communal grazing lands in many parts of the former homelands, cattle in these areas could produce less than the 8 kg of dung per head per day shown in Table 6.1, mainly as a result of poor feeding[16].

The daily manure yields of pigs are summarised in Table 6.2. A distinction is made between yields which have been recorded on commercial farms, and those pertaining to farms in underdeveloped areas. No large discrepancy is apparent between the manure yields of pigs on commercial farms and those in underdeveloped areas. According to Werner *et al* (1989: 22) the live weight of pigs varies between 30 and 75 kg. While a pig on a commercial farm may have a live weight of 68 kg (Weller and Willetts 1977: 30), live weights of 50-60 kg are used for pigs in underdeveloped areas (Werner *et al* 1989: 22).

Table 6.2: Manure yields of pigs.

Quantity	Commercial farms	Underdeveloped areas
Manure as % of live weight	5.1-7.4	5
Dung as % of live weight		2
Urine as % of live weight		2.5-3
Manure yield (kg/day)	5	
Dung yield (kg/day)		2-5

Sources: Fulford (1988: 35); Funke *et al* (1984: 1); Hobson (1990: 98); Jewell *et al* (1981: 114); Sasse (1988: 11); Weller and Willetts (1977: 31); and Werner *et al* (1989: 22).

The daily excreta yields for poultry are summarised in Table 6.3. The yields for laying hens and broilers were recorded on commercial farms, while the general figures include yields pertaining to underdeveloped areas. A laying hen on a commercial farm may have a live weight of 2.25 kg (Weller and Willetts 1977: 31), while live weights of 1.5-2 kg are used for chicken in underdeveloped areas (Werner *et al* 1989: 22).

[16]Personal communication with Francois Esterhuyse of the Faculty of Agriculture, University of Pretoria.

The daily manure yields pertaining to horses, sheep and goats which are presented in Table 6.3 mainly refer to animals in underdeveloped areas, while the yields as percentage of live weight refer to all areas. According to Werner *et al* (1989: 22) the live weight of sheep and goats varies between 30 and 100 kg, with males being up to twice as heavy as females.

Table 6.3: Excreta/manure yields of poultry and various animals.

	Yield as % of live weight	Daily yield (kg/day)
Laying hens	3.2-6.2	0.10-0.144
Broilers	7.9	0.04-0.06
Poultry (general)	4.5-6	0.075-0.08
Horse dung		10
Sheep manure	3-4.4	
Sheep/goat dung	3	1
Sheep/goat urine	1-1.5	

Sources: Aubart and Fauchille (1983: 32); Fulford (1988: 35); Funke *et al* (1984: 1); Hobson (1990: 98); Jewell *et al* (1981: 114); Sasse (1988: 11); Weller and Willetts (1977: 30) and Werner *et al* (1989: 22).

6.2.2 Properties of fresh manure

Some of the properties of different animal manures and excreta are summarised in Tables 6.4 and 6.5. These generally apply to the fresh manure as it is produced by the animals. Considerable variation in the C/N ratios of the different substrates is evident in these tables. The C/N ratio of the dung produced by cattle in underdeveloped areas, which feed on straw and dry grass, tend to be much higher (i.e. up to 35) than that of cattle in developed countries where more protein-rich foods are provided (i.e. 20 or less) (Fulford 1988: 36). According to Werner *et al* (1989: 22) urine has a C/N ratio of 0.8, and a TS content of 5 %.

Table 6.4: Properties of cattle and pig manure.

	Dairy cattle manure	Beef cattle manure	Cattle dung	Pig manure	Pig dung
Total solids (%)	12-13	9-14	16-25	8-14	16-25
Total solids (mg/ℓ)	82 300			81 700	
Volatile solids (%)	10	10	13	6-12	12-14
Volatile solids (% of TS)	81-83	79	77	81-82	80
Volatile solids (mg/ℓ)	59 400			61 500	
COD (mg/ℓ)	140 000 - 185 000	80 000 - 132 000		100 000 - 150 000	
COD:VS	1.05	1.12		1.19	
Total nitrogen (mg/ℓ)	3 700			5 400	
Ammonia-nitrogen (mg/ℓ)	1 900			2 900	
pH	7.8			6.8	
C/N ratio			10-35		9-14

Sources: Fulford (1988: 35); Funke *et al* (1984: 3); Hobson (1990: 98); Jewell *et al* (1981: 114); Sasse 1988: 11); Weller and Willetts (1977: 33); and Werner *et al* (1989: 22).

Table 6.5: Properties of poultry excreta and dung of various animals.

	Laying hens	Broilers	Poultry	Horse dung	Sheep/goat dung
Total solids (%)	25-50	25	21-48	25-30	30-32
Total solids (mg/ℓ)	191 100				
Volatile solids (%)			16-21	15	20
Volatile solids (% of TS)	58-71		64-77		
Volatile solids (mg/ℓ)	140 800				
COD (mg/ℓ)			170 000		
COD:VS			1.28		
Total nitrogen (mg/ℓ)	14 700				
Ammonia-nitrogen (mg/ℓ)	5 700				
pH	6.7				
C/N ratio			5-8	25	20-30

Sources: Aubart and Fauchille (1983: 32); Fulford (1988: 35); Funke *et al* (1984: 3); Hobson (1990: 98); Jewell *et al* (1981: 114); Sasse (1988: 11); Weller and Willetts (1977: 33); and Werner *et al* (1989: 22).

6.2.3 Manure available for biogas production

Not all the manure that is produced at a farm is available for use in a biogas plant. The quantities and the properties of the waste that is available for this purpose depend on farming practices such as the housing of animals, the cleaning of pens etc. In general only manure that is produced by animals in confinement is available for use in a biogas plant, as the collection of dung in the open veld would result in a considerable additional work burden for farmers, which would generally be unacceptable. In India the collection of dung from the veld is practised by poor families who own biogas plants, but this seems to be the exception (Kijne 1984: 45). The proportion of the manure which can be collected, depends on the following factors:

- The degree of confinement of the animals, i.e. whether they are kept in a shed, kraal or animal house throughout the day, or graze in the veld for part of the day.

- The type of floor covering used in the shed or kraal, e.g. concrete or soil.

- Whether provision has been made for the collection of the manure, e.g. in the form of slatted floors and collection channels.

All of the manure (i.e. dung and urine) is available only if the animals are in permanent confinement, and if the floors are designed for collecting urine as well as dung. For example, if cattle are confined only during the night, only about 33-50 % of the manure that is produced, can be collected (Werner *et al* 1989: 22). According to Werner *et al* (1989: 8) the installation of a biogas plant on small farms often goes hand in hand with a transition to either overnight stabling or zero-grazing practices.

If cattle are kept on unpaved floors, no urine can be collected, while an estimated 10 % of the dung produced is also lost (Werner *et al* 1989: 41). Moreover, the dung collected from earth floors contains soil and stones which accumulate in the biogas plant and reduce the active volume. Ideally the animals should therefore be kept in paved stables or kraals which provides for the collection of all the dung and the urine, and ensures that the manure remains clean. According to Werner *et al* (1989: 27) the paving of stable floors also reduces the chance of hoof disease in cattle and generally improves the quality of animal husbandry. In Tanzania the installation of a biogas plant is usually accompanied by the paving of the stable to reduce the work involved in feeding the plant (Sasse *et al* 1991: 10). In the former homelands cattle are often confined during the night in kraals with earth-floors. The possibility of paving the kraals should be considered when biogas technology is implemented in these areas. However, when this matter was discussed with the Mathabela family in Gazankulu (see Section 9.4.3), they expressed concern about the comfort of the cattle if a concrete floor was provided in the kraal.

Estimated quantities of the cattle manure which can be collected on smallholdings in underdeveloped areas under different confinement conditions are presented in Table 6.6. The total solids content of the manure is also provided, as the quantities available cannot be compared in a meaningful manner unless this is known. According to Werner *et al*

(1989: 27) the dung collected from earth-floor kraals can have a TS content as high as 60 %, depending on when it is collected. The weight of the cattle was assumed to be 200 kg, and the manure yield was assumed to be 10 % of the live weight of the cattle, half of which comprised dung (see Table 6.1). The losses due to part-time stabling and unpaved floors were based on that reported by Werner *et al* (1989: 41).

Table 6.6: Quantities and total solids content of available manure for cattle in underdeveloped areas kept under different confinement conditions.

Duration of confinement	Floor condition	Material collected	Quantity collected (kg/head/day)	Total solids content (%)
24 hours	paved	fresh dung, urine	20	11
24 hours	unpaved	fresh dung	9	16
24 hours	unpaved	dry dung	5	30
overnight	paved	fresh dung, urine	11	11
overnight	unpaved	fresh dung	5	16
overnight	unpaved	dry dung	3	30

Sources: Werner *et al* (1989: 41) and Theilen (1990: 18).

According to Kijne (1984: 65) estimates of manure availability based on calculations often exceed the actual quantities available. It is therefore advisable to measure the actual quantities available if possible. For example, in the case of a smallholding with a small number of animals the quantity of manure which is available on a daily basis can be measured for three consecutive days to obtain an average. Trace (1990: 65) measured the quantity of dung that could be collected from the kraal belonging to the Mathabela family in October 1990. He found that an average quantity of approximately 2 kg of dung was available on a daily basis per head of cattle, with a TS content of approximately 24 % (i.e. 0.5 kg of TS was available per head of cattle per day). This is significantly less than the quantities presented in Table 6.6 for similar conditions (i.e. cattle confined overnight on an unpaved floor), which are equivalent to 0.8-0.9 kg of TS per head of cattle per day. This illustrates the importance of measuring the actual quantities of dung which are available at a particular site if this is possible.

The quantities and the properties of the manure which is available may vary during different seasons and years as a result of changes in grazing practices or conditions which are related to climatic variations (Kijne 1984: 65). For example, the TS content of the dung collected from the kraal of the Mathabela family varied significantly (16-32 %) during the period it was monitored (see Section 8.2.5).

The quantity of waste that would required by a farmer for biogas production would generally depend on his energy requirements, the nature of the waste available as well as the operating conditions, e.g. the digester temperature. However, it is possible to set a lower limit to the quantity of waste that would be required per day to produce gas sufficient for the domestic needs of a household. According to Sasse *et al* (1991: 13) this comprises about 50 kg of fresh cattle dung or 35 kg of fresh pig manure. In Tanzania it has been found that, in order to meet these requirements, a minimum number of three milk cows or ten adult pigs should be permanently confined in a stable, or a minimum of nine head of local cattle should be stable-bound for part of the day (Sasse *et al* 1991: 13). However, based on the quantities and the total solids content of the dung which have been collected from the Mathabela family's cattle kraal, a minimum number of 17 cattle might be required by smallholders in the former homelands under prevailing conditions, i.e. if the cattle are kept in earth-floor kraals during the night, and graze on communal lands during the day. However, it would be advisable to determine the quantities, and possibly the total solids content, of the dung produced by local cattle in each particular area, as the grazing conditions could differ substantially in different areas.

If intensive livestock keeping is practised on a farm, the waste available for use in a biogas plant may comprise manure combined with bedding material or litter, and possibly spilled feed, which would increase the quantity as well as the TS content of the waste. For example, Werner *et al* (1989: 22) maintains that the waste from cattle stalls with litter can include 2-3 kg of litter per animal per day in addition to the manure. According to Hobson (1990: 98) the waste from poultry houses with litter, such as sawdust, can have a TS content of 50-80 %. Generally any straw used as bedding should be reduced in size to 2-6 cm before it is utilised (Werner *et al* 1989: 28). Sawdust should preferably not be used as bedding, as it does not digest well and results in excessive scum formation (*ibid*).

On the other hand, water which is added to the waste, such as cleaning water, incidental spillage from drinking nipples or troughs, and rain water, could result in the significant dilution of the waste (Weller and Willetts 1977: 32). Intensive forms of animal husbandry often involve excessive water consumption for cleaning, leading to large quantities of wastewater which are very dilute. For example, at the piggery where one of the demonstration units was installed, the wastewater utilised in the digester was found to have a total solids content of the order of 1 % (see Section 8.5.5). Generally the waste would be more solid if adequate absorbent bedding and sufficient roof cover are provided, if surface water run-off is properly channelled, and if scraping rather than washing-down techniques are used for cleaning (*ibid*).

6.2.4 Properties of plant residues

The properties of plant residues which are relevant to the production of biogas are provided in Table 6.7.

Table 6.7: Properties of plant residues.

	Total solids (%)	Volatile solids (% of TS)	C/N ratio
rice straw	89	93	
wheat straw	82	94	80-140
corn straw	80	91	30-65
straw/husks			70
fresh grass	24	89	12
grass/leaves			35
vegetable residue	12	86	35

Sources: Fulford (1988: 35); Sasse (1988: 11); and Werner *et al* (1989: 23).

6.3 Water requirements of biogas systems

As discussed in Section 3.3.1, the total solids concentration of the slurry in a simple biogas plant should in most cases be between 6 and 13 %. As the TS content of the waste available for biogas production is often much higher (see Section 6.2.3), it is usually necessary to dilute the waste by adding a liquid such as water or urine. The quantity of liquid that should be added to the waste would depend on the total solids content of the waste and the desired TS content of the slurry. Common mixing ratios for cattle or pig dung with water vary between 1:3 and 2:1 by volume (Werner *et al* 1989: 40). A minimum of 50 ℓ of water would be required to operate a small biogas plant. However, according to Werner *et al* (1989: 28) the water required for the feeding of a digester could be reduced by 30-40 % if the liquid component of the digester effluent is used to dilute the fresh waste.

The need for easy access to water close to a biogas plant is clearly an important consideration when the installation of a plant is considered. In Tanzania this is a prerequisite for the installation of plants on smallholdings (Sasse *et al* 1991: 13). In the rural areas of the former homelands water is generally collected on foot from communal supply points, which can take the form of protected springs, handpumps, stand-pipes etc. Considerable variation exists in different areas with regard to the distances which have to be traversed by mainly women and children to collect water, but these can be as far as several kilometres. The availability of water in a particular area can also be affected by seasonal or longer-term climatic variations. For example, during the 30 months that the plant at the Mathabela family was monitored, water had to be fetched over distances ranging from 20 m to 2 km, which resulted at least partly from to the drought experienced in the area (see Section 9.4.4).

6.4 Climatic suitability for the implementation of the technology

The suitability of different parts of South Africa for the implementation of biogas technology, based on ambient and soil temperatures, has been discussed in Section 3.3.2. Another climatic factor which can serve as an indicator of the suitability of particularly farming areas for the production of biogas, is the rainfall characteristics of such areas. The rainfall in an area has an impact on the type of farming practised, and therefore the nature of the agricultural waste that would be available, as well as the availability of water in the area. This is particularly true in underdeveloped areas such as the former homelands, where smallholders generally do not have access to adequate water resources for agricultural purposes, particularly in times of drought.

The different rainfall regions in South Africa, based on mean annual rainfall, are shown in Figure D.2 in Appendix D. According to Werner *et al* (1989: 21) areas with an annual rainfall of 800-1500 mm generally have the greatest potential for the utilisation of biogas technology, as water is usually available throughout the year. Livestock farming can be more intensive under these conditions, allowing for the collection of manure, while combined livestock and crop farming is common (*ibid*). The application of biogas technology is also possible in areas with an annual rainfall of 400-800 mm, although these areas are characterised by a long dry season and livestock farming tends to be extensive, both of which place restrictions on the utilisation of the technology (Werner *et al* 1989: 21). The conditions in regions with a higher or lower rainfall than the above tend to be unfavourable or completely unsuitable for biogas technology.

However, rainfall is clearly not an absolute measure of the suitability of an area for the implementation of biogas technology, as the availability of agricultural wastes and water at a specific location depends on a variety of factors. For example, by means of the suitable development of available water resources, sufficient water can be made available for purposes such as irrigation, the cleaning of animal houses and animal watering in areas where rainfall is relatively low.

6.5 Labour requirements of biogas systems

An important consideration when a biogas plant is installed on a farm or smallholding, is the additional labour that would be required to operate and maintain the plant. Generally it would be necessary to minimise the work required to feed the plant in particular, as biogas plants have failed in the past because of the extra work load this has involved (Kellner and Lwakabamba 1985: 315).

A biogas plant should therefore be positioned as close as possible to the source of the waste, such as an animal kraal. On smallholdings the manure produced by a small number of cattle could be collected by hand to feed a plant. However, as this is can be a tedious process, a different approach has been taken in Tanzania (Sasse *et al* 1991: 42), which is also recommended by Werner *et al* (1989: 27): When a biogas plant is installed, the stable or kraal is provided with a concrete floor, which is fitted with a collection channel directly connected to the mixing box of the biogas plant. If possible, provision is made for the manure to flow directly into the mixing box by exploiting a natural gradient over a short distance. Although this increases the total cost of a plant, it reduces the work involved in feeding the plant, and therefore helps to ensure regular feeding. This arrangement is regarded as one of the main reasons for the acceptability of the technology in Tanzania (Neumann 1990: 1). In the case of large biogas plants, such arrangements would be essential to minimise the labour costs related to the feeding of the units.

6.6 Uses of biogas technology other than energy production

In this study the production of biogas to meet energy needs has been the main function of biogas technology which has been considered. However, aspects such as the stabilisation of organic waste and the production of organic fertiliser could also be of considerable importance on farms and smallholdings. Werner *et al* (1989: 25) points out that small farms on which livestock and crop farming are practised together in a balanced manner, are particularly suitable for the application of biogas technology, as the availability of manure for the feeding of the digester would be combined with a need for the digested slurry as fertiliser. Sasse *et al* (1991: 52) suggests that the cultivated fields should be located next to the biogas plant and that, if possible, provision should be made for distribution channels by which the slurry could flow by gravity to the fields.

In the former homelands arable fields which have been allocated to rural households are generally located at a distance from the homesteads, mainly as a result of "betterment planning" which have been implemented in these areas. The utilisation of digested slurry on these fields would generally not be feasible, because of the considerable labour and transport inputs that would be required. KwaZulu appears to be the only former homeland where the majority of rural households still live in a scattered manner, and where arable fields are therefore located close to the homesteads[17], while a significant proportion of rural households in the Transkei live under similar conditions. The regular use of slurry on the fields might therefore be feasible in parts of KwaZulu and to a lesser extent in the Transkei. However, a fairly common practice in the former homelands is the growing of vegetables and, in some cases, fruit trees in gardens which are adjacent to homesteads (see Section 9.4.6 for discussion on use of digested slurry by Mathabela family), and which can be quite large in some cases. The most feasible application for digested slurry in the former homelands would therefore probably be in homestead gardens of this nature.

On large farms the main consideration when biogas technology is implemented, is often the waste treatment aspect, particularly in European countries where legislation on pollution is generally stringent. Generally the feasibility of utilising biogas technology as a waste treatment option would depend on the effectiveness and cost of a biogas system compared to alternative waste treatment systems. In addition, the digested slurry could be a valuable resource if used as organic fertiliser or animal feed.

[17]Personal communication with Professor Bembridge of the University of Fort Hare.

6.7 Former homeland areas with potential for the application of biogas technology

In this section an attempt will be made to identify the areas in the former homelands which have the greatest potential for the implementation of biogas technology, based on climatic considerations as well as cattle figures. According to Bembridge (1990: 18) approximately 84 % of the ± 16.72 million hectares of land in the former homelands which were available for agriculture, was only suitable for grazing. At present there are an estimated 5.7 million head of cattle in these areas (*ibid*).

The potential of an area for the application of biogas technology is best measured by the number of smallholders who own more than a certain number of cattle. As discussed in Section 6.2.3, this figure may be as high as seventeen in the former homelands. An attempt was made to obtain detailed figures on cattle ownership in the former homelands by contacting the various Departments of Agriculture, but information was only received from a small number of them. These figures, together with others obtained from various sources, are presented in Table 6.8. The figures on KwaZulu have been calculated by combining information from various sources and are therefore expected to be less accurate than the other figures.

As statistics on cattle ownership could not be obtained for all the former homelands, it was decided to use the ratio of cattle to people in each district of the former homelands as a relative measure of its potential for the implementation of the technology, as this would provide for the comparison of all the areas on an equal basis. However, actual cattle ownership figures would need to be considered before the real potential of an area could be assessed, as the cattle to people ratio could conceal skewed ownership patterns.

The ratio of cattle to people was calculated for all former homeland districts using population and cattle figures that were obtained from the Development Bank of Southern Africa. The most recent cattle and population figures pertaining to a specific year were used in each case, but not all of the ratios were calculated for the same year. A list of the districts in the former homelands which have the *highest* ratios of cattle to people (> 0.4) is presented in Table G.1 in Appendix G. A rough evaluation of the climate in each district, based on temperature and rainfall characteristics, is also indicated. The only former homelands represented in this table are Transkei, KwaZulu, Bophuthatswana, Gazankulu and Kangwane, i.e. none of the other former homelands had districts where the cattle to people ratio was greater than 0.4. However, if one considers the actual cattle ownership figures in Table 6.8, it would appear that parts of the Transkei, KwaZulu and Bophuthatswana have considerably greater potential for the implementation of the technology than the most favourable areas in Gazankulu and Kangwane.

Table 6.8: Percentages of households in some districts of the former homelands who own more than ten head of cattle.

Homeland district	Percentage of households (%)
BOPHUTHATSWANA	
Western areas	33
GAZANKULU	
Mhala	7
Ritavi	5
Malamulele	3
Giyani	6
KANGWANE	
Eerstehoek	6
Kamhlushwa	9
Nsikazi	2
KWAZULU	
Ubombo	15
Nongoma	22
Hlabisa	25
Mahlabatini	23
Enseleni	7
Nkandla	13
Inkanyezi	9
Ongoye	7
Mapumulo	9
Ndwedwe	6
TRANSKEI	
Qamata	18
Emgcwe	30
Qumbu	16
Umtata	3

Sources: Development Bank of Southern Africa; Departments of Agriculture in the former homelands; Bembridge (1984: 361); and Tapson and Rose (1984: 44).

6.8 Conclusions

Considerable variation is found in the quantities and properties of the manure produced by animals, which can be attributed to factors such as the breed, age and live weight of the animals as well as their diet. The quantities of manure produced by animals can be estimated on a live weight basis, as this usually provides a realistic estimate. However, not all the manure which is produced on farms and smallholdings would be available for use in a biogas plant, while the properties of the available material may differ considerably from the properties of fresh manure. On smallholdings where a limited quantity of manure would be available, it is advisable to measure the actual quantities available to ensure that the installation of a biogas plant would be feasible. The quantities and the properties of the waste that is available would depend on farming practices such as the housing of animals, and the cleaning of stables.

Based on the quantities and properties of the dung which could been collected from the cattle kraal of the Mathabela family in Gazankulu, a minimum number of 17 cattle might be required by smallholders in the former homelands in order to utilise small-scale biogas technology. This is considerably more than the required minimum number of cattle in other countries for similar conditions, i.e. the confinement of the cattle for part of the day only. This could be attributed in part to the deteriorated state of the grazing lands in parts of the former homelands, which would result in relatively low manure yields. However, it would be necessary to assess the situation in particular areas, as the grazing conditions could differ substantially.

A minimum of 50 ℓ of water would be required per day to operate a small biogas plant. However, the water required for the feeding of a digester could be reduced by 30-40 % if the liquid component of the digester effluent is used to dilute the fresh waste. The rainfall characteristics of an area can give an indication of the suitability of the area for the implementation of biogas technology, particularly in underdeveloped areas, as rainfall has an impact on the agricultural practices as well as the availability of water in an area.

Generally it would be necessary to minimise the work required to feed a biogas plant, particularly in the case of large-scale plants. This can be done by providing the cattle kraal or stable with a concrete floor, which is fitted with a collection channel directly connected to the mixing box of the biogas plant. The most viable applications of biogas technology on small farms are found where mixed farming is practised, so that the availability of manure for the feeding of the digester is combined with a need for the digested slurry as fertiliser. In the former homelands the most feasible use for digested slurry would appear to be as fertiliser in home gardens, which can be fairly large. It would appear that parts of the Transkei, KwaZulu and Bophuthatswana have the greatest potential for the implementation of biogas technology in the former homelands, based on cattle figures in these areas.

CHAPTER 7
UTILISING HUMAN EXCRETA FOR BIOGAS PRODUCTION

7.1 Introduction

The connection of toilets to biogas plants which are mainly operated on agricultural wastes is fairly common in some of the countries where biogas technology has been implemented. For example, in China fixed-dome plants are used to produce gas from crop wastes and animal manure and latrines have been connected to the digesters to improve rural hygiene (Van Buren 1979: 18). More or less the same situation is found at the home of University of Pretoria's professor Dieter Holm (1986), where the main feed material is the manure produced by four horses, to which the waste from the toilet and kitchen are added. However, in these digesters the human excreta form a relatively small component of the total feed material.

The focus in this chapter will be on the use of human excreta as the main substrate in biogas plants, which would be the case if the technology is applied at institutions such as schools (see Section 2.3). For example, in Burundi biogas systems have been installed at eighteen secondary schools, one prison and one military camp, while hospitals were also considered as potential locations (Hoffmann 1992: 16). A biogas plant which utilises human waste should primarily be seen as a sanitation system with the additional benefit of gas production. The treatment and safe disposal of the excreta should therefore be given the highest priority when a system is designed and implemented. Various aspects of this application of biogas technology will be considered here, including the quantities and properties of human excreta, as well as the waste which is produced in ablution facilities, suitable plant designs for the digestion of human waste, and the implementation of two types of systems for the utilisation of human excreta, one of which would involve the disposal of the digested slurry at the institution concerned.

7.2 Produced quantities and properties of human excreta

The quantities as well as the composition of the excreta produced by humans depend on factors such as living conditions, diet, health, occupation and the working environment (De Villiers 1986: 6). In Table 7.1 the quantities of excreta that are produced by different categories of people on a daily basis, are presented. According to Werner *et al* (1989: 22) the quantities of faeces and urine that are produced daily by human beings, comprise 1 % and 2 % respectively of the live weight of a person.

Some of the properties of human excreta and wastewater produced in households, which are of importance when its use as substrate for the production of biogas is considered, are summarised in Table 7.2. The calculated values presented in the table were determined using the produced quantities and properties of human excreta reported by Werner *et al* (1989: 22). As is evident from the table, the calculated values differ substantially from the reported properties of night soil.

Table 7.1: Quantities of human excreta produced.

Quantity produced/person/day			Comments
faeces (kg)	urine (ℓ)	excreta (ℓ)	
0.5-0.8	1-1.6		based on calculations by live weight (50-80 kg)
0.5	1.0		
0.35	1.2		rural adults in the Third World
0.25	1.2		urban adults in the Third World
		1.5	including cleansing material (adult)
0.13-0.52			adults in developing countries
0.4	0.2 / sitting		
0.06-0.07			young child in South Africa
0.12-0.18			older child in South Africa
		0.8-0.9	primary school children in Natal

Sources: Danawade and Joglekar (1991: 4); De Villiers (1986: 6); Edwards (1992: 140); Mang (1992: 21); and Werner et al (1989: 22).

Table 7.2: Properties of human excreta and wastewater.

Material	TS (%)	VS (%)	C/N ratio	COD (mg/ℓ)
solids	20-23	14-15	8	
urine	5	2	0.8	
night soil (solids and urine)	5	3.4	6-10	
solids and urine (calculated)	10		3	
typical household wastewater	100-375 mg/ℓ	75-200 mg/ℓ		
wastewater mixed with kitchen waste				1 200 - 18 000 mg/ℓ

Sources: Danawade and Joglekar (1991: 4); Hoffmann (1992: 16); Mang (1992: 21); National Academy of Sciences (1977: 41); Werner *et al* (1989: 22); and Barnett, Pyle and Subramanian (1978: 51).

The low C/N ratio of human excreta, and particularly the faeces and urine in combination, is of concern when this material is to be used in biogas systems. The calculated C/N ratio of human excreta is very low, indicating that ammonia toxicity may be a problem in a digester (see Section 3.4.2). The addition of water or other substrates (e.g. plant matter or animal manure) to a biogas plant would therefore probably be required to reduce the ammonia concentration of the slurry, particularly as the TS concentration of faeces and urine in combination seems to be relatively high (e.g. the calculated value is 10 %).

A particular concern when human excreta is used in biogas systems, is the health risks posed by the substrate. The following four groups of pathogenic organisms are generally associated with human faecal material (Barnett *et al* 1978: 30) (National Academy of Sciences 1977: 54):

- viruses which cause illnesses such as poliomyelitis, infectious hepatitis, gastroenteritis and respiratory illness
- protozoa causing amoebic dysentery
- bacteria causing typhoid fever, paratyphoid, bacillary dysentery, cholera, tuberculosis, enteritis and salmonellosis
- helminths comprising roundworm, pinworm, sheep liver fluke, bilharziasis, whipworm, tapeworm and hookworm

The occurrence of pathogens in excreta generally depends on the extent to which these illnesses are endemic to an area.

7.3 Quantities and properties of total waste produced

The quantities and properties of the waste from toilet or ablution facilities which enter a biogas plant, would depend on the nature and design of the facilities, as well as the manner and the frequency with which it is utilised. The quantities presented in Table 7.1 could be used to estimate the total quantity of excreta that would enter the digester on a daily basis, but this is likely to result in an overestimation. Inquiries made at the Mzimhlophe Secondary School in KwaNdebele (see Section 8.3) have indicated that a relatively small percentage of the pupils used the toilets at the school for defecation on a daily basis.

Some cleaning material would generally be mixed with the excreta. In addition, the water used to flush toilets, as well as water from hand basins, baths, showers and laundry facilities (i.e. grey water) could add to the total volume of the waste. The quantities of grey water that are typically produced at ablution facilities would lead to the excessive dilution of the waste entering a digester. This can be reduced by piping most of the grey water directly to a soak-away or another disposal facility. Urinals can also be provided for men to reduce the flushing of toilets. In addition, toilets with a flush volume of 5 ℓ or less can be used, e.g. a low-flush toilet pan or a tipping-tray pedestal such as those available from the companies Vaal Potteries and Kemclad respectively. However, it is important that the flushing provides for adequate cleaning of the toilet bowl to prevent further addition of water by users.

According to Mang (1992: 21) the daily quantity of water that would enter a digester via the toilets could be estimated by assuming that one flush of a toilet occurs per day for each person using the facilities, but he points out that this should be seen as a low average. He recommends the use of a flush volume of 7-10 ℓ for sizing purposes. In Burundi the sizing of digesters at schools was reportedly based on quantities of 10 ℓ per person per day where low-flush systems were used on an individual basis, and 5 ℓ per person per day if flushing was done in a collective way (Hoffmann 1992: 17).

7.4 Plant designs suitable for the digestion of human waste

All the simple biogas plant designs which have been considered in this study (see Chapter 4) have been used for the digestion of human excreta, e.g. in Burundi (Hoffmann 1992: 16). Because of the health risks associated with human excreta (see Section 7.2), the plants most suitable for the utilisation of human excreta are those which completely enclose the digesting material, such as the fixed-dome plant, the floating-drum plant with a water-jacket, and a closed digester with a separate gas holder. The gas drum used on the floating-drum plant with a water-jacket would need to be resistant to corrosion, as the gas produced from human excreta contains greater quantities of hydrogen sulphide than in the case of agricultural substrates. The HDPE drum installed at the University of Pretoria's experimental farm, with the external guide system provided at this plant, would probably be well-suited for this purpose.

7.5 Operational aspects

Fulford (1988: 58) has pointed out that the digestion of night soil is poor if no provision is made for the breaking up and mixing of the faeces, which tend to settle or float in a digester. He therefore suggested that the wastewater from toilets should be collected in a settling pit, from where the solids should be pumped into the digester, while the excess liquids should be allowed to drain into a soak-away. Such a system was installed at the school in KwaNdebele where one of the demonstration units was built (see Section 8.3). However, as the use of a sludge pump adds to the costs as well as the complexity of a biogas system, this type of system would not be generally feasible.

A special inlet has to be provided if other substrates such as plant residues or animal waste will be added to a digester. There could be heavy scum formation if kitchen waste is added (Mang 1992: 20), but this could be reduced by placing a grease trap in the pipeline. Generally plant material would need to be shredded very well to prevent blockages in the system, and to reduce scum formation as far as possible. The main operating problem experienced in Burundi with biogas digesters utilising human excreta, has been blockages (Hoffmann 1992: 17). However, less problems of a serious nature have occurred in the biogas systems compared to septic tanks, which have been attributed to the fact that the biogas plants are operated on a continuous basis, i.e. effluent containing solids leaves the digester on a regular basis. At the school in KwaNdebele where a pilot-plant was installed, various objects were found in the pipeline to the septic tank, including plastic bottles and bags, and large rags which caused blockages in the sludge pump (see Section 8.3.6). Such objects could also result in blockages when toilets are directly coupled to biogas plants. Generally provision would need to be made to unblock the inlet and outlet pipes of a digester.

7.6 Gas production

Generally very low gas production rates are achieved in biogas plants utilising human excreta. Hoffmann (1992: 18) found that the gas production recorded at six institutions in Burundi varied between 35 % and 242 % of the expected gas production, based on rates of 17-27 ℓ of biogas per person per day. The volumetric gas production rate (VGPR) of the plants varied between 0.02 and 0.13 m^3 of gas per m^3 of digester volume per day, which is significantly less than the VGPR of 0.25 m^3/m^3/day which can be achieved in plants utilising agricultural waste (Theilen 1990: 17). The reasons for the variation in the gas production achieved in the different plants, included differences in the dilution of the waste, the addition of kitchen waste in some cases, and the existence of blockages and leaks in digesters (Hoffmann 1992: 18). A 6 000 ℓ-biogas digester in India, which was operated at a hydraulic retention time of 8 days, achieved a VGPR which fluctuated between 0.09 and 0.15 m^3/m^3/day during the course of a year (Danawade and Joglekar 1991: 4).

7.7 Biogas systems with local disposal of effluent

Two different types of biogas systems which utilise human excreta are discussed here. The first of these comprises a continuously operated biogas plant, from which effluent containing solids is displaced on a regular basis as fresh material enters the digester. Such a system therefore requires the handling and disposal of the digester effluent at the institution where it is implemented, possibly by using it as fertiliser. The second type of system is operated in a similar way to septic tanks and anaerobic digesters, and does not require the handling and disposal of solids from the digester by the institution involved.

The most important consideration when implementing a system which involves the local disposal of the effluent, is the need to ensure the effective destruction of pathogens in the digester to reduce the risks involved.

7.7.1 Destruction of pathogens

In Table 7.3 the conditions which provide for the destruction of some of the pathogens in human excreta are given. Generally most of the organisms are destroyed at digester temperatures above 35 °C and retention times longer than 14 days, the main exception being the eggs of the Ascaris lumbricoides (roundworm) (Barnett *et al* 1978: 59). Xihui (1988: 4) reported that, unless special measures were taken, the digester effluent still contained 5 % of the parasitic ova present in the waste. Aerobic bacteria like shigella and spirochetes are killed relatively quickly in biogas plants because of the lack of oxygen, while facultative bacteria such as paratyphoid B are able to survive longer (McGarry and Stainforth 1978: 82). In addition, Hoffmann (1992: 17) reported that Salmonella were completely destroyed in digesters operated at long retention times (60-100 days).

Table 7.3: Destruction of pathogens during anaerobic digestion at different temperatures and retention times.

Organism (Disease)	Temperature (°C)	Retention time (days)	Percentage destroyed
Salmonella spp. (salmonellosis)	8-25 22-37 35-37	44 6-20 7	100 82-96 100
Salmonella typhosa (typhoid fever)	22-37	6-20	99
Myobacterium tuberculosis (tuberculosis)	30	not available	100
Ascaris lumbricoides ova (roundworm)	9-18 9-18 8-25 29 35-37	10-95 100 100 15 36	21-37 52.9 53 90 98.8
Schistosoma ova	9-18 ± 23 8-25 35-37	40-43 > 14 7-22 7	100 100 100 100
Hookworm ova	9-18 9-18 8-25 35-37	40 70-100 30 10	93.4 99-100 90 100
Shigella spp. (bacillary dysentery)	8-25 35-37	30 5	100 100
Poliovirus 1 (poliomyelitis) Polioviruses	35 35-37	2 9	98.5 100
Parasite cysts, excluding Ascaris	30	10	100

Sources: National Academy of Sciences (1977: 55); McGarry and Stainforth (1978: 72); Werner *et al* (1989: 31) and Barnett *et al* (1978: 59).

As can be seen from Table 7.3, high destruction rates can generally be achieved at lower temperatures if the retention time is long enough, the main exception being the Ascaris ova. As simple biogas plants are usually unheated and therefore operate at temperatures below 35 °C, high pathogen destruction rates in these plants can only be achieved by means of long retention times. According to Mang (1992: 21), depending on the location (i.e. the temperature) of the biogas plant, the retention time in completely mixed continuous digesters (see Section 3.2.2) should be at least 80-100 days to enable the safe utilisation of the effluent. He recommended a retention time of 80 days at a temperature of 27 °C. In Burundi, where the effluent was utilised as fertiliser in 60 % of the cases discussed, retention times of 100 days and 60 days were used at environmental temperatures of 18-22 °C and 26-34 °C respectively (Hoffmann 1992: 17). The minimum retention time set in China where the effluent is commonly used as fertiliser, was 30 days (Xihui 1988: 4).

Digesters utilising human excreta are often adapted to ensure that maximum reduction of the pathogens in the effluent is achieved. For example, fixed-dome digesters are often provided with an outlet in the form of a pipe which leaves the digester halfway from the bottom. This ensures that the effluent is drawn from the more dilute layer of slurry in the middle of the digester, between the scum layer on top and the settled sludge at the bottom (Xihui 1988: 4). According to Werner *et al* (1989: 31) the scum and settled sludge together contain about 95 % of the ova and pathogens in the digester. Similarly, it has been found in China that the effluent from the middle layer contains only 1.8-6.2 % of the ova present in the fresh material added to the digester (Xihui 1988: 4). In Burundi digesters utilising human excreta has been fitted with a central wall to provide for the accumulation of the solids in the first compartment, thereby increasing the retention time of the solids in the digesters (Hoffmann 1992: 16). In China the same principle has been applied in multi-stage fixed-dome digesters, which either consist of two or three digesters in series, or a digester fitted with one or two partitions (Xihui 1988: 6). Parasitic ova reduction rates of up to 99.95 % has been achieved in digesters operating in series (*ibid*).

It has been found that parasitic eggs and other pathogens are destroyed at a faster rate at higher concentrations of ammonia, e.g. the average lifespan of schistosoma ova was reduced from 13 days to 5 days when the ammonia concentration in the slurry increased from 900 mg/ℓ to 1700 mg/ℓ (McGarry and Stainforth 1978: 79). It should therefore be possible to achieve higher pathogen destruction rates by reducing the quantity of water that enters a digester, thereby providing for the development of higher concentrations of ammonia. Xihui (1988: 4) reported that the ova reduction rate was increased to more than 95 % by collecting and storing the excreta for 30 days in a small chamber between the toilets and the digester. The higher destruction rate probably resulted from the higher ammonia concentration which developed in the undiluted excreta, as compared to the digester (McGarry and Stainforth 1978: 79). However, this method is probably only feasible if the number of people using the toilet facilities are limited, e.g. if one toilet is connected to a plant mainly operated on animal wastes.

In general it is probably advisable to monitor the effluent from digesters operated at low temperatures and/or short retention times for the presence of pathogenic organisms, in order to assess the risks posed by the effluent.

7.7.2 Sizing of the digester

The size of the digester, as with simple biogas plants generally, is determined by the volume of the waste which is expected to enter the digester per day on average, and the required retention time. Mang (1992: 21) suggests that the calculated digester volume should be increased by 15 % to provide a safety margin, and to allow for the build-up of sludge in the digester. The demands which could be placed on the capacity of the digester by periods of peak usage, as well as the possible need for a small increase in the capacity of the unit in the future, should also be considered (*ibid*).

Because of the long retention times required to ensure the destruction of most of the pathogens in human excreta, it is critical that the volume of water which enters the plant is reduced as far as possible, otherwise the size of the digester could become excessive. Mang

(1992: 21) gives an example of the sizing of a biogas plant utilising human excreta which illustrates this problem. He calculated that the required volume of a digester serving 100 people would be approximately 88 m^3, including a safety margin of 15 %. One of the assumptions he made, was that 8 ℓ of flushing water would enter the digester per day for every person using the facilities. The estimated gas production rate, based on theoretical considerations, was 4 m^3/day (*ibid*).

Such a biogas plant would not be economically viable either as a sanitation or an energy system. The biogas digester would be much larger than a conventional septic tank or anaerobic digester which serves the same number of people (typically 35 m^3[18]). It would also constitute an extremely inefficient biogas plant, with an estimated volumetric gas production rate (VGPR) of 0.05 m^3 of gas per m^3 of digester per day. While the gas production could be doubled if kitchen waste was added (Mang 1992: 21), this would still only give a VGPR of 0.1 m^3/m^3/day.

7.7.3 Utilisation of the effluent

The public health hazards associated with the use of the digester effluent as fertiliser depend on three factors (Barnett *et al* 1978: 30) (National Academy of Sciences 1977: 53):

- the incidence of viable pathogenic organisms in the fresh excreta
- the survival rates of these organisms in the digester
- the storage time of the effluent prior to its application to the land

The survival of pathogens in a digester therefore does not present an insurmountable obstacle to the use of the effluent as fertiliser, as these organisms continue to die off once the effluent has been removed, both during the storage of the slurry, and when it has been applied to the soil (National Academy of Sciences 1977: 53).

The effluent from the biogas digester is generally treated before it is used as fertiliser. Chinese biogas plants operated on night soil, crop residues and animal manure, are usually emptied once or twice a year to remove accumulated solids. The scum and settled sludge are treated further before being used as fertiliser, one of the reasons being to ensure that 95-100 % of the Ascaris ova is destroyed (Xihui 1988: 4). The pretreatment can take the form of composting for a period of 5-7 days at a temperature of 50-55 °C (*ibid*). Special measures are needed to prevent the breeding of insects during this process (*ibid*). According to Barnett *et al* (1978: 30) most of the pathogenic organisms in human faeces are destroyed during aerobic composting if temperatures exceed 60 °C for longer than 0.5-1 hour. Nevertheless, the utilisation of the effluent from a biogas plant operated on human waste would in many cases not be desirable because of the health risks attached, particularly if no proper control is exercised over the system.

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[18]Personal communication with Francois Smith of the Division of Building Technology (CSIR).

7.8 Biogas systems with solids accumulation

The second type of biogas system which utilises human excreta would be designed and operated in a similar way to septic tanks and anaerobic digesters. This system therefore differs substantially from the continuously operated biogas plant discussed above. The digester would be provided with an overflow which leads to a soak-away, and solids would be prevented from leaving the digester by providing a T-piece or baffle at the outlet. The soil at the location would therefore need to be suitable for the construction of a soak-away. Generally there would be no need for members of the local institution to handle solids from the digester. The accumulated solids in the digester would be removed at specific intervals when the digester is desludged. This service could be provided by the tankers responsible for the emptying of septic tanks and anaerobic digesters. However, as this service is not generally available in rural areas, the possible implementation of this type of biogas system would be more limited than the first one. The volume of the digester would be determined by the volume of wastes which enter the digester per day on average, a hydraulic retention time which is sufficient to allow the solids to settle (typically 2 days), as well as the period between consecutive desludgings of the digester (typically 3 years)[19].

The most appropriate design for this application would probably be a digester with a separate gas holder, as this would allow for the inclusion of design aspects of septic tanks, e.g. the baffle or T-piece preventing solids from leaving the digester. The fixed-dome plant would probably be unsuitable for this purpose, as it is likely that some of the settled solids on the bottom of the digester would be brought into suspension by the movement of the digesting slurry to and from the displacement tank, thereby increasing the possibility of solids leaving the digester through the overflow.

7.9 Economic viability and social acceptability

In Burundi it has been found that the benefits of the biogas plants installed at institutions, presumably in terms of savings on energy and possibly fertiliser costs, were in most cases higher than the maintenance costs, but that the total investment costs could not be recovered (Hoffmann 1992: 17). However, the cost of a biogas plant was found to be significantly lower than that of a septic tank for the same institution.

Evidence from African countries suggests that the social acceptability of biogas technology utilising human waste is not of serious concern. For example, in Burundi no problems had been experienced with the social acceptance of biogas produced from human excreta, or the use of the effluent as fertiliser (Hoffmann 1992: 15). According to Kyu and Muturi (1986: 154), while there is no tradition of using night soil for agricultural purposes in Africa, human waste utilisation is not taboo as is the case in some parts of Asia for religious or other reasons. A survey that was conducted in Kenya indicated that most rural people responded

[19]Personal communication with Francois Smith of the Division of Building Technology (CSIR).

positively to the utilisation of human excreta for the production of biogas (*ibid*). However, evidence presently available suggests that the use of human excreta would not be acceptable to many rural households in South Africa (see Section 9.3). For example, the Mathabela family were not in favour of the use of human excreta in a biogas plant, particularly if the slurry was to be used as fertiliser.

7.10 Conclusions

A biogas plant which utilises human excreta should primarily be seen as a sanitation system with the additional benefit of gas production. The properties of human excreta, such as its low C/N ratio and the tendency of the solids to either float or settle, present some difficulties when it is utilised as a substrate in biogas plants. In addition, the wastewater from ablution blocks would generally be too dilute to provide satisfactory gas production, and would also lead to excessive sizes for biogas plants. Measures would therefore be required to reduce the quantities of water entering a digester. The relatively low volumetric gas production rates which are achieved in biogas plants utilising human excreta, compared to agricultural systems, can be attributed to a combination of these factors. The possible health risks posed by pathogenic organisms associated with human excreta need to be considered in the design and operation of biogas systems. The most suitable plant designs for the utilisation of human excreta are the fixed-dome plant, the floating-drum plant with a water-jacket, and a digester with a separate gas holder, as all of these provide for the enclosure of the digesting material.

Two different types of biogas systems which utilise human excreta can be implemented, the first comprising a continuously operated biogas plant, i.e. digested material containing solids would leave the plant on a regular basis. The second system would be operated similarly to a septic tank, i.e. solids would be prevented from leaving the plant. The first system would require the disposal of the effluent at the institution where the biogas plant is installed. The destruction rates of pathogens in the digester would therefore be of particular concern. Higher destruction rates are generally achieved at high temperatures or long retention times. In simple biogas plants which are operated at ambient temperatures, retention times of 80-100 days would generally be required to ensure satisfactory destruction rates. It would probably be advisable to monitor the effluent from such plants for the presence of pathogenic organisms, in order to assess the risks posed by the effluent. The disposal and possible utilisation of the effluent would require proper management to ensure that risks are minimised. On the other hand, biogas plants operated similarly to septic tanks would not involve the handling of solids by the institution concerned, but would require desludging every few years.

In most rural areas it would be necessary to implement biogas systems which would require the disposal of the effluent at the institution involved, as desludging services would generally not be available. As most schools in rural areas would probably not have the resources required to ensure proper management of the effluent, the application of biogas technology at these schools does not seem very promising under current conditions.

CHAPTER 8

PILOT PLANTS INSTALLED DURING THE STUDY

8.1 Introduction

In this chapter the five pilot plants that were installed as part of this study, will be described in great detail. Basic information on these plants is summarised in Table 8.1. Photographs of the plants are presented in Appendix C. General matters concerning the plants, such as the purposes of each unit, the selection of the sites, and problems which were experienced in each case will be considered. In addition, the results of the monitoring of some of these plants will be discussed.

Table 8.1: Summarised information on the pilot plants.

Location	Rural family	Peri-urban school	Experimental farm	Commercial farm	Smallholding
Plant design	floating-drum plant	digester with separate gas holder	floating-drum plant	flexible cover plant	fixed-dome plant
System of operation	partly mixed	plug-flow	partly mixed	plug-flow	partly mixed
Digester size (m^3)	9	9	8	10	9
Substrate used	cattle dung	human excreta	cattle dung	piggery effluent	cattle dung, human excreta
Construction completed	October 1990	August 1991	October 1991	March 1992	February 1993

As discussed in Section 1.2, a certain tension was present in the way that the project funded by the Department of Mineral and Energy Affairs (DMEA) had been conceived, i.e. with the demonstration of the technology being given precedence above its development to a satisfactory level of performance. For example, the first two pilot plants had to be installed at "real-life" locations in the former homelands, with no opportunity to test these designs, and to acquire some on-hand experience of the technology beforehand. This had an important effect on the decisions that were made regarding the designs of the pilot plants (see Section 4.3 in particular), as the risks of failure involved, as well as other risks, such as the health risks associated with human excreta that were discussed in Section 7.2, had to be reduced as far as possible.

Some of the factors which impact on gas production, such as substrate characteristics and operational parameters, were monitored at the biogas plants which had been commissioned successfully during the study. The degree of monitoring that was performed varies greatly for the different plants, depending on the period for which each plant had been in operation during the study period. For example, in the case of the fixed-dome plant no monitoring results have been included here, as only the construction of the plant had been completed by the end of the study. Only the plant that was built at the Mathabela family could be monitored for any significant period.

8.2 The demonstration plant at a rural family

The first biogas plant that was provided for in the DMEA project, had to be built at the homestead of a rural family in one of the former homelands. The main aim was to do a preliminary assessment of the feasibility of biogas as a domestic energy source among low-income rural households in these areas. The objectives of the project were as follows:

- to demonstrate biogas technology to rural people
- to assess the social acceptability of the technology among these people
- to assess the technical feasibility of its implementation by rural families
- to test the design and evaluate its performance
- to assess the economic viability of the design

8.2.1 Selection of the area and the family

It was decided to obtain the cooperation of an organisation based in one of the former homelands, as most of these areas were located a great distance from Pretoria. Douglas Banks, an engineer who was employed by the University of the Witwatersrand Rural Facility (WRF) at the time, had shown an interest in the study. An agreement was subsequently reached with this organisation to implement this part of the study jointly. The WRF is situated along the road to the Orpen Gate of the Kruger National Park, about 15 km east of Klaserie in the Eastern Transvaal lowveld (see Appendix A). The decision to cooperate with the WRF limited the area in which this project could be implemented to the surrounding districts of Lebowa and Gazankulu.

Preliminary discussions were held with a few families in the area, to assess their interest in biogas technology. Freddy Mathabela, a young man who was occasionally employed by the WRF as an interpreter, expressed a keen interest in owning a digester. He had been exposed to the technology during a rural energy audit in the area and had also seen a small-scale pilot digester at the WRF. The Mathabela family live in the village of Timbavati, in the Mhala district of Gazankulu, approximately 2 km from Acornhoek in the Eastern Transvaal Lowveld. The approximate location of their homestead is indicated in Appendix A. The family owned nine head of cattle at the time, which were kept in a kraal at night. Their main source of energy was firewood which was either collected or bought. The circumstances of the family are discussed in great detail in Section 9.4. This family seemed ideal for the purposes of the project, as they owned a relatively large number of cattle, while water was available from a stand-pipe close to the homestead. The family also had a low formal income, i.e. R 200 per month (1990 rand), and therefore provided the opportunity to investigate the possible utilisation of the technology by people in a fairly poor socio-economic grouping.

A meeting was held with the family during which the project was explained to them. Specific attention was given to the implications of the project for them in terms of the labour required for construction, the scale of the construction work it would involve, the monitoring that would be required and the publicity that would result from it. It was unclear to what extent the explanation was successful, especially as it was difficult even for members of the project team to visualise the full implications of the project. The family showed some interest in the project and did not express any major concerns about participating in it. However, they found it difficult to visualise a biogas plant, particularly one of the size under discussion, and seemed to take a "we'll wait and see" approach. The family appeared to be willing to participate in the project more from a sense of trust in the people who had approached them, than a personal understanding of the technology. They agreed to assist with the construction and the monitoring of the digester.

8.2.2 Design and sizing of the plant

It was decided to build a floating-drum plant rather than a fixed-dome plant at the Mathabela homestead for the reasons discussed in Sections 4.2 and 4.3. The construction of a fixed-dome plant presented considerable difficulties, and the DMEA-funded project did not provide for the development of the skills required for this purpose. As the main purpose of the plant was to demonstrate the technology to potential users, it was deemed essential to reduce the risks of failure which could result in a negative attitude to the technology from the onset. The biogas plant that was built at the Mathabela homestead is shown in Figure C.1 in Appendix C. It comprises a ferrocement digester which is fitted with a painted mild steel gas drum. This design was discussed in Section 4.2 and design drawings are provided in Appendix B.

The size of the plant was determined conservatively, as no local information on gas production or gas use was available. It was felt that an inadequately sized system could influence the attitude of the family towards biogas adversely, as it might not fulfil their expectations of gas production. The plant was designed to contain about 9 m^3 of slurry, based on a retention time of 100 days and a feeding rate of 90 ℓ of slurry per day. The gas drum made provision for the storage of 2.6 m^3 of biogas, which was the expected gas production rate in summer, based on gas production rates which were recorded in Botswana (Khatibu 1983: 5).

8.2.3 Installation of the plant

The Mathabela family undertook to arrange the digging of the hole for the digester as part of their contribution to the project. A cylindrical hole of 2.8 m depth was required, but it was only dug to approximately 2 m, because a hard layer of semi-weathered rock was encountered at this depth, and the digging had been done manually. This resulted in the digester being higher above ground level than intended. Because of the height of the digester above ground level, changes had to be made to the original design to ensure that the mixing box would not be too high for feeding purposes. The height of the mixing box relative to the digester, as well as the level of the slurry outlet were therefore both reduced. The construction work was done mainly by CSIR personnel assisted by the Mathabela family, while a local builder was employed to do some of the brickwork. After the plant had been installed, the Mathabela family undertook to pack soil around the mixing box and the digester to provide for easier feeding and to improve the insulation of the digester. Another consequence of the height of the digester above ground level, was that the PVC inlet and outlet pipes were not completely buried. Mr Mathabela therefore undertook to cover the exposed parts of the pipes with mortar to protect them from UV-radiation.

The initial filling of the digester proved to be difficult, as large quantities of dung and water had to be collected manually within a fairly short period. Although there was a stand-pipe less than 100 m from the Mathabela homestead, water was not available there at the time and had to be transported from another stand-pipe approximately 2 km away. Dung was collected from the nearby cattle kraals of friends and relatives of the Mathabela family by means of a light-delivery vehicle. As only small quantities of dung could be obtained from each of these kraals, it had not been possible to collect enough dung to provide for the optimum solids concentration in the digester (see Section 3.3.1).

A leak was detected after the digester had been filled, which necessitated the partial emptying of the digester to repair the joint between the outlet pipe and the digester wall. When the pit had to be refilled, an arrangement was made for 5000 ℓ of water to be delivered by a water tanker owned by the local hospital.

The gas drum was built in the metal workshop at the Mapulaneng Technical College in Acornhoek, where a few staff members assisted voluntarily with its construction. Scum breakers were fixed inside the drum, and a paddle stirrer was provided to enable some mixing of the slurry inside the digester. The drum was painted on the inside and outside with a primer and two coats of bitumen paint. The drum weighs approximately 200 kg, and eight people were required to place it in position. A gas valve was attached to the gas outlet on the drum, and a nylon-reinforced garden hose was installed overhead for about 10 m to a small rondavel used as a kitchen. A water trap in the form of a manometer was provided at a low point in the gas pipeline.

Gas production started within a few weeks of filling the digester (i.e. in December 1990), and gas burners were installed once the safety of using the gas had been ascertained. The family were provided with two low-pressure cast-iron burners with a flame diameter of approximately 11 cm (see Figure C.7 in Appendix C). Based on recommendations by the Rural Industries Innovation Centre (RIIC) in Botswana[20], the burner jets were enlarged to 2 mm to allow for the low gas pressure (i.e. 75 mm water pressure at the plant). The Mathabela family were instructed on the operation of the plant, the use of the gas burners and the possible dangers associated with the use of gas. They were requested to contact the

[20]Personal communication with Mr Richard Tsitloe of the RIIC.

WRF if any difficulties were experienced. The family insisted on the construction of a fence around the biogas plant to prevent vandalism or accidental damage to the plant. A notice informing passers-by of the biogas plant was erected by the family, and no-smoking signs were painted on the digester.

8.2.4 Construction costs of the plant

A breakdown of the construction costs of the biogas plant is provided in Table 8.2. The labour costs had to be estimated as the construction was mainly done by CSIR personnel with the aid of voluntary labour. The following wages that were paid in rural areas in 1992[21] were used to calculate labour costs:

- R 15/day for unskilled labour
- R 30/day for skilled labour, e.g. brick laying and plastering
- R 50/day for skilled technical work, e.g. welding

Labour costs for 1990 were then estimated by assuming annual inflation rates of 14.4 % in 1990 and 15.5 % in 1991 respectively[22]. The labour required for the digging of the hole for the digester has not been included. As is evident from the table, the materials cost of the gas drum was fairly high, mainly as the gas drum had been somewhat oversized.

Table 8.2: Construction costs of the Mathabela biogas plant.

	Labour (1990 rand)	Materials (1990 rand)	Total (1990 rand)
Digester	660	1270	1930
Gas drum	270	990	1260
Piping and accessories	20	160	180
Total	950	2420	3370

8.2.5 Monitoring of the plant

Limited monitoring of the Mathabela family plant was undertaken during the project to assess the utilisation of the plant by the family and to relate the measured gas production rate to other system parameters.

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[21]Personal communication with Dave Still, an engineer employed by the Division of Water Technology (CSIR) at the time.

[22]Official inflation rates were obtained from the Central Statistical Services.

8.2.5.1 Properties of dung and slurry composition

Samples of the fresh dung which had been collected from the kraal, the mixture of dung and water added to the digester, the slurry inside the digester, and the effluent from the plant, were taken at irregular intervals. The samples were analyzed in terms of total solids and volatile solids content as well as COD, and the results are presented in Table 8.3. One set of samples was analyzed during each month indicated in the table.

Table 8.3: Results of laboratory analyses of manure and slurry samples obtained from the kraal and digester at the Mathabela homestead.

Sample	Date	COD (g/ℓ)	Total solids	Volatile Solids	VS as % of TS
Fresh dung collected from kraal	February 1992		17 %		
	September 1992	279	312 g/ℓ	231 g/ℓ	74
	October 1992	182	32 % 335 g/ℓ	24 % 254 g/ℓ	76
	February 1993	147	169 g/ℓ	141 g/ℓ	83
Feed material mixed by operator	December 1990	136	113 g/ℓ	77 g/ℓ	68
	February 1992		11 %		
	July 1992	98	89 g/ℓ	71 g/ℓ	80
	October 1992	96	11 % 119 g/ℓ	9.2 % 96 g/ℓ	81
Slurry inside digester (1.5 m down)	February 1992		6.4 %		
Slurry inside digester (2 m down) at inlet side	July 1992	62	55 g/ℓ	42 g/ℓ	76
Slurry inside digester (2 m down) at outlet side	July 1992	31	56 g/ℓ	42 g/ℓ	75
Effluent collected from outlet pipe	December 1990	9	5.6 g/ℓ	3.4 g/ℓ	61
	February 1992	92	7.3 %		
	July 1992	63	67 g/ℓ	50 g/ℓ	75
	February 1993	59	79 g/ℓ	59 g/ℓ	75

At first the samples were sent to an analytical laboratory at the CSIR in Pretoria. However, the results obtained from the first set of samples that was analyzed during 1991 proved to be totally inaccurate. The reason appeared to be that the analytical equipment used at this laboratory were unsuited for the analysis of material with a relatively high total solids content. Difficulties were also experienced with the dispatchment of the samples from Wits Rural Facility to Pretoria, and arrangements were therefore made with a laboratory in Nelspruit to do the analyses. However, this was never realised, as the responsible person at the laboratory failed to cooperate with Wits Rural Facility. Finally, a group at the CSIR which conducted similar analyses for their own purposes on substrates with relatively high total solids content, agreed to assist with the analyses. However, as a result of these difficulties no results were obtained during 1991.

The results summarised in Table 8.3 can be compared with the results of the analyses which had been conducted by Trace (1990: 63) using dung collected from the Mathabela kraal in October 1990:

- total solids content of fresh dung: 24 %
- volatile solids of fresh dung as percentage of total solids: 72 %

Some of the variations evident in the table can be attributed to the inhomogeneity of the material that was analyzed, e.g. the difference in the volatile solids content as percentage of total solids between fresh dung and the feed material mixed by the operator in October 1992. However, considerable variation is evident in the total solids content (and correspondingly in the volatile solids content) of the fresh dung during the period involved, which can be attributed mainly to climatic variations which affect the availability of water and fresh fodder to the cattle (see Section 6.2.3). The total solids content of the dung tended to be lower in the late summer (17 % in February 1992 and approximately 16 % in February 1993) which corresponds to the rainy season, while high total solids concentrations were measured after the winter (24 % in October 1990 and 32 % in October 1992) which is the dry season. The TS content of the dung was particularly high in October 1992, when the drought in the area was at its most severe. It is of interest that, in spite of these variations in the TS content of the dung, the concentration of the slurry prepared by the operators of the plant remained fairly constant at approximately 11 % TS during most of the period involved.

As discussed in Section 8.2.3, the digester was filled initially with a very dilute slurry. This is reflected by the low TS concentration (< 1 %) of the effluent in December 1990, just a month after the digester had been filled for the first time. By the beginning of 1992 the effluent concentration had increased to approximately 7 % TS due to the consistent feeding at relatively high slurry concentrations. The total solids content of the slurry samples obtained from the digester itself was generally slightly lower than that of the effluent. This was probably due to stratification inside the digester, partly as a result of the low concentration of the slurry (Fulford 1988: 35). The effluent would have contained more of the solids which tend to settle on the bottom of the digester compared to the middle of the digester from where these samples were taken.

8.2.5.2 Operational parameters

Basic monitoring of the biogas plant was undertaken by members of the Mathabela family assisted by the WRF[23] during the first twenty months of operation. An attempt was made

[23]Most of the results and general information presented here have been provided by Douglas Banks, who was employed at the WRF during most of this project, and was the principal contact between the project staff and the Mathabela family.

to monitor the feeding rate (i.e. the quantity of slurry added to the digester per day on average), the digester temperature and the gas production rate achieved. The quantities of slurry added to the plant and the digester temperature were in most cases measured and recorded by family members. One of the sons in the family, Freddy Mathabela, was specifically responsible for the monitoring of the plant. Gas production was most often measured by personnel of the WRF, although this task was also performed by family members during the latter part of the monitoring period.

Feeding rate

The potential value of this monitoring exercise has been limited by the fact that a reliable record of inputs to the digester could not be obtained, for a number of reasons. Firstly, the feeding of the plant was not always recorded by family members. Secondly, the records of the number of containers of dung and water respectively that were mixed and added to the digester, were not always accurate, as the feeding tasks were performed by different people, some of whom were neither numerate or literate. Moreover, a variety of containers were used to collect dung and water, the size of which were not always known. Attempts were made to establish practices that would ensure greater accuracy, such as the use of particular containers to collect dung and water, but these were difficult to enforce. As one of the main purposes of the study had been to assess the response of the family to the technology, it was seen as important that monitoring was conducted with as little interference from the outside as possible, to allow the family to integrate the operation of the plant into their everyday lives. Based on the records kept by family members of the quantities of dung and water that were added to the digester, it was estimated that the slurry was mixed in a ratio of 1.4-1.8 parts dung to one part water by volume.

During the latter part of the monitoring period (i.e. in 1992) the effluent displaced from the plant was also measured and recorded, in an attempt to obtain a more accurate assessment of the feeding rate. A container of known dimensions was placed at the outlet and the record keeper was asked to measure and record the effluent level in the container and to empty it when necessary. The effluent production rate was expected to correspond fairly closely to the feeding rate, as the 1991/92 rainy season had been very poor, so that rain catchment by the digester would not have increased the effluent volume significantly, while the reduction in the volume of the slurry during the digestion process was expected to be less than 10 % (Werner *et al* 1989: 30). The reliability of the effluent measurements appeared to be somewhat higher than in the case of the recorded inputs to the plant.

An average feeding rate was calculated for every period during which fairly reliable measurements of either the slurry input or the displaced effluent could be obtained. These are presented in Figure 8.1[24], together with the recorded gas production rate and digester temperatures, which are discussed below. The considerable variation in the feeding rate probably reflects the changing nature of actual feeding practices, although the inaccuracy of

[24]The results reported here have been compiled by Douglas Banks of the WRF who was responsible for the monitoring of the Mathabela biogas plant.

the measurements would also have contributed. An average feeding rate was calculated for the entire monitoring period, based on the quantities presented in the figure, and this was found to be 30 ℓ of slurry per day. Although the degree of uncertainty involved is very high, this provides some indication of the order of magnitude of the feeding implemented by the family. However, it is likely that the actual feeding rate was lower than this, as the calculations were based on the records which were available, while feeding may have been less regular during times when no records were kept. This feeding rate corresponds to a retention time of 300 days, which is extremely long compared to the recommended retention times for simple biogas plants of 60-80 days (see Section 3.3.3). The biogas plant was therefore completely underutilised.

The actual feeding rate has therefore been significantly lower than the feeding rate of approximately 90 ℓ/day at 8 % TS (equivalent to ± 65 ℓ/day at 11 % TS) which had been expected. The main reason for the low feeding rate appeared to be the small quantities of dung produced by the cattle owned by the Mathabela family. Based on the quantities of cattle dung that were collected by Trace (1990: 65) from the kraal of the Mathabela family in October 1990 (see Section 6.2.3), a feeding rate of ± 40 ℓ/day at a total solids content of 11 % could have been achieved by the family if all the available dung was collected on a daily basis. However, observations during the project had indicated that dung had not been collected every day, for reasons such as a lack of water and the straying of the cattle (see Section 9.4.3).

Temperature

The digester temperature was measured using a thermometer attached to the end of a pole that was pushed into the digester through the outlet pipe. This measuring technique clearly did not provide for great accuracy in the measurements, but it was regarded as satisfactory under the circumstances.

The temperatures that were recorded during the monitoring period are presented in Figure 8.1. The fluctuations in the recorded temperatures can be attributed to a combination of actual changes in the digester temperature and inaccuracies in the measurements. A general trend is evident in the recorded temperatures, which corresponds to seasonal changes. Maximum temperatures were recorded between January and March in 1991 as well as 1992, while minimum temperatures were recorded in the winter months. As discussed in Section 3.3.2, 20 °C is the threshold temperature above which satisfactory rates of digestion and gas production can be achieved. The climate in the area is clearly well-suited to the production of biogas, as the recorded digester temperature remained above 20 °C during most of the monitoring period, dropping below this value only during the winter of 1991.

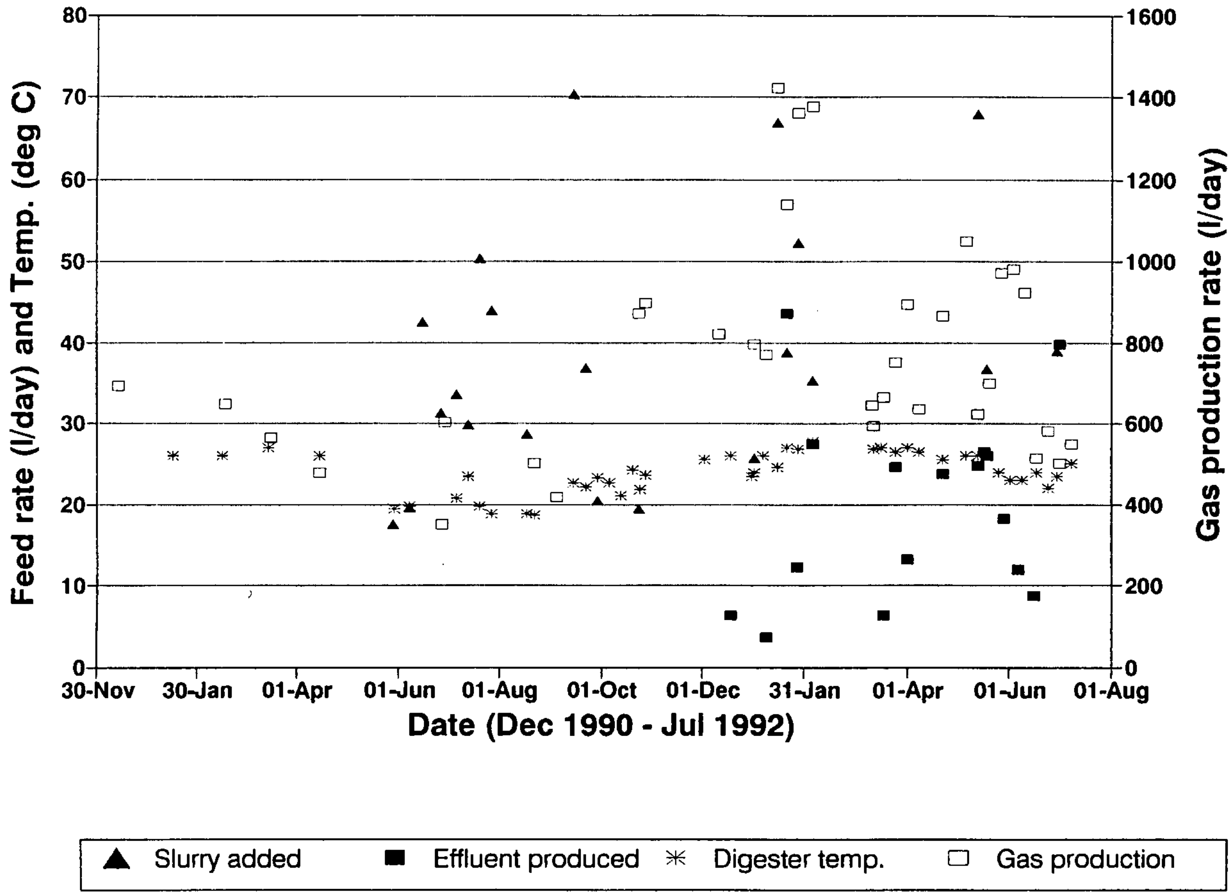

Figure 8.1: Measured feeding rate, digester temperature and gas production of the Mathabela biogas plant.

Gas production

Gas production was measured by closing the gas valve on the gas drum and noting the rise in the height of the gas drum relative to the level of the slurry in the digester, which fluctuated slightly. The waiting period involved was usually more than ten hours. The gas production rates measured during the monitoring period are presented in Figure 8.1. The considerable variation in the measured rates can probably be attributed mainly to inaccuracies in the measurements, although actual changes in gas production would also have occurred. However, some of the fluctuations involve dramatic changes within relatively short periods, e.g. the sharp increase in January 1992, which would have been highly unlikely.

A general trend is evident in the gas production rates measured, which roughly corresponds to the seasonal changes in digester temperature. Gas production was low from the onset, probably because of the low total solids content of the slurry. The lower gas production rates recorded during the winter of 1991 can be attributed to the low digester temperature. A possible reduction in the feeding rate during the dry winter season may also have contributed, but this is not evident from the records. Gas production was highest during the summer and autumn of 1992, and seemed to decrease once more as winter approached. An average gas production rate was calculated for the entire monitoring period, using the measured rates given in Figure 8.1, and was found to be approximately 770 ℓ/day. As insufficient data were available, monthly gas production rates could not be calculated.

Prior to November 1991, when the gas deflecting ledge was installed, an estimated 15 % of the gas that was generated, escaped through the annular gap between the drum and the digester wall. However, because of the high degree of uncertainty in the measured gas production rates, it has not been possible to assess whether the installation of the ledge actually improved the collection of gas in the plant.

8.2.6 Conclusions

The installation of the plant at the Mathabela homestead provided for the evaluation and improvement of the floating-drum design comprising a ferrocement digester and a mild steel gas drum, as discussed in Section 4.2. The low average feeding rate that was achieved by the family during the first twenty months of the project, indicated that the plant was completely underutilised. This can be attributed to a large extent to the small quantities of dung produced by the cattle owned by the family.

The plant also provided the opportunity to monitor the experience of the Mathabela family regarding the technology over a period of time, and to gauge the response of other people in the surrounding area to the technology. These matters are discussed in Chapter 9. The experience gained during this project has provided some valuable insights regarding the requirements for the successful implementation of biogas technology by smallholders in the former homelands (see Section 9.6).

8.3 The demonstration plant at a rural school

The second biogas plant that was provided for in the DMEA project, had to be installed at a school in one of the former homelands. The main aim was to do a preliminary assessment of the use of biogas as an energy source at schools in these areas. The objectives of the project were as follows:

- to demonstrate the technology to pupils, school staff and parents
- to assess the social acceptability of the technology among school staff and pupils
- to assess the technical feasibility of producing biogas from human excreta at schools
- to test the chosen design and evaluate its performance
- to assess the economic viability of the design

8.3.1 Selection of the school

Because of the complexities involved when human excreta is utilised in biogas plants (see Chapter 7), it was decided to build the plant reasonably close to Pretoria to provide for the direct involvement of the CSIR throughout the project. Restrictions on the implementation of projects funded by the National Energy Council[25] in the independent states, such as Bophuthatswana, therefore meant that the project could only be implemented in KwaNdebele.

In order to fulfil its demonstration purpose, the plant had to be built at a school which had a real need for the gas. A secondary school provided with a homecraft centre was regarded as the most suitable location for a biogas plant, as such a centre would require a relatively large quantity of energy for cooking and possibly refrigeration purposes. In addition, the use of gas had to be a more attractive option to the teachers and pupils concerned than the fuels available at the time, as this would create an incentive for the operation of the biogas plant. For this reason a school which did not have access to electricity was preferred.

In an attempt to obtain a suitable location, a few schools were visited in Tweefontein, KwaNdebele, a peri-urban area which developed along the main road that passes KwaMhlanga (see Appendix A). The Mzimhlophe Secondary School, which is located about 70 km from Pretoria, was the third school that was visited, and the first of those visited which had a homecraft centre. At the time 900-1000 pupils were enrolled at the Mzimhlophe Secondary School. The homecraft centre was equipped with coal stoves, but according to the homecraft teachers, Ms Mohuba and Ms Seitesho, this was not ideal, as it resulted in delays when classes had to use the stoves in quick succession. This was due to the need to stoke the stoves each time, and the waiting period involved before the stoves reached the desired temperature. The teachers also expressed the need for a fridge which would enable them to store perishable foods during school hours. A gas fridge was available at the school, but was not being used, presumably because of a lack of funds. The school therefore seemed to provide an ideal demonstration site, as it had a clear need for the gas.

The possibility of implementing the project at the school was discussed with the principal, Mr David Matsepe, who expressed an interest in the technology and a willingness to be involved in the project. Discussions were subsequently held with the homecraft teachers and pupils at the school. The teachers were enthusiastic about the use of the gas for cooking purposes at the centre, but the pupils had some reservations about the preparation of food on gas produced from human excreta. However, they were interested in the technology, and felt that it could be used to conduct science experiments. After the technology had been explained thoroughly to the pupils, they agreed to "give it a chance".

The school was equipped with an on-site sanitation system which comprised low-volume (5 ℓ) flush toilets that were connected to a 40 m^3 septic tank located about 60 metres from the ablution block. The ablution block was divided in four sections, for male and female pupils and teachers respectively, and a total of 21 toilets and 4 urinals were provided. However,

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[25]At the time the project was funded by the National Energy Council, which was subsequently absorbed into the Department of Mineral and Energy Affairs.

the existing sanitation system was not seen as an obstacle to the installation of a biogas system (see below).

8.3.2 Planning of the system at the school

During the initial planning stage the biogas plant was seen as part of an integrated system of waste management and effluent re-use that was to be implemented at the school. The following system was envisaged: settled solids would be pumped from the septic tank into a biogas plant, from which the gas would be extracted, while the digester effluent would flow into a composting compartment which provided fertiliser for a vegetable garden. A solar-powered sludge pump would be used, and the project would therefore serve to demonstrate both the use of solar energy and biogas technology. The principal indicated that alterations to the existing sanitation system could be made in order to implement the project.

This plan was reviewed in May 1992 when the author assumed project leadership. The main concern was that insufficient information was available on the potential health risks posed by the digester effluent. In addition, the acceptability of the proposed system to the school caretakers, who would have been responsible for the handling of the effluent, was doubted. The safe disposal of the effluent without direct human intervention therefore became an important consideration in the design of the system. It was argued that the first biogas plant utilising human excreta had to be implemented under controlled conditions, which enabled the assessment of the health risks presented by the effluent and the development of measures aimed at reducing the risks involved.

At this stage of the project the possibility of changing the location of the pilot plant to a school where pit latrines were still being used, was considered. This would have enabled the installation of a simple system with direct connections between the toilets and the biogas plant. However, it was noted that Fulford (1988: 58) expressed concern about the poor digestion of human faeces if toilets are directly connected to a digester. He recommended that the faeces should be collected in a settling pit from where it should be pumped into the digester, to ensure that it was properly macerated. Another important consideration was the fact that the existing septic tank at the school provided a means of disposing of the digester effluent. The biogas system could therefore be implemented without resulting in significant health risks at the school.

It was therefore decided to continue with the project at this school. The pipeline between the ablution block and the septic tank would be intercepted and the solids collected in a settling pit. After the excess liquid had been allowed to drain, the solids would be pumped into the biogas plant once a day, using the solar-powered sludge pump. The outlet of the biogas plant would be connected to the septic tank pipeline below the settling pit to allow the digester effluent to flow to the septic tank. The digester effluent would be monitored for pathogens to assess the health risks it posed. Human faeces was to be the main feed material used in the biogas plant. In addition, grass obtained from the school terrain was to be chopped up and composted before adding it to the biogas plant in order to increase the C/N ratio of the substrate.

8.3.3 Design and construction of the biogas plant

A detailed discussion of the design and construction of the biogas plant built at the school is provided in this section rather than in Chapter 4, as it is not a typical design which could be compared with plants which have been built in other parts of the world. In addition, the satisfactory operation of the plant had not been verified, as will become evident from the discussion.

As mentioned above, one of the aims of this project was to design and test a biogas plant that would be suitable for use at rural institutions such as schools. The matters that need to be considered when designing a biogas plant for the digestion of human excreta were discussed in Chapter 7. The two considerations which determined the choice of the design used at the school were the need to provide for the enclosure of the digesting material at all times, as well as the need to provide for the maximal destruction of pathogens in the excreta. It is particularly important at a public institution such as a school, to ensure that the digesting material is properly enclosed so as not to risk the outbreak of disease. The three designs which satisfy this criteria are the fixed-dome plant, the floating-drum plant with a water-jacket and a digester with a separate gas holder. The former could not be installed at the school for the same reason which prohibited its installation at the Mathabela homestead, namely the difficulty to build the dome successfully (see Section 4.3).

There were also some concerns about the suitability of the floating-drum design with a water-jacket. The mild steel gas drum that was used on the Mathabela biogas plant was the only reliable gas drum available at the time. However, this drum was prone to corrosion and would have required regular repainting (probably on an annual basis), and replacement after a few years. According to Fulford (1988: 47) a drum which is not maintained properly may need replacement after five years. As the biogas produced from human excreta is more corrosive than that produced from animal waste, the lifetime of the drum was expected to be considerably shorter than the estimated 10-15 years (Werner *et al* 1989: 62). The possible outcome in the long term if the drum was not maintained well and not replaced when necessary, i.e. the exposure of the slurry in the plant to the surrounding environment, was regarded as unacceptable. By comparison, a closed digester provided with a separate gas holder would ensure that the digesting slurry remained enclosed at all times. The main concern regarding this design was the fact that it was expected to be more expensive than the other designs.

The second matter that was considered in particular when designing the pilot plant at the school, was the need to provide for the maximal destruction of pathogens in the excreta. This was seen as particularly important because the removal of the digested sludge by means of a tanker would not be possible in many rural areas, which meant that the digester effluent would have to be handled manually (see Section 7.7). As discussed in Section 7.7.1, the destruction of pathogens in unheated biogas plants is primarily dependent on the retention time of the digesting material. While the design retention time of a digester is related to its total volume as well as the volume of fresh material that enters the digester on a regular basis, the actual retention time of the digesting material also depends on the shape of the digester. As discussed in Section 3.3.3, the actual retention time in a plug-flow digester is much closer to the design retention time than in the case of mixed digesters. It was therefore concluded that a digester which provided for plug-flow digestion would be most appropriate for the digestion of human excreta, as the pathogens in the excreta would be more effectively destroyed. The decision was therefore made to install a plug-flow digester with a separate gas holder at the school. Design drawings for the biogas plant are provided in Appendix B.

The digester design was similar to a conventional septic tank design, comprising a single-brick structure with a reinforced concrete roof slab. However, as shown in the design drawings in Appendix B, the basic rectangular shape was modified to reduce the angular joints in the gas space which would be more difficult to render gas-tight (Sasse 1988: 31), and to improve the structural properties of the digester walls. A half-brick wall was built along the long axis of the digester to divide it into two equal parts, and the inlet and outlet pipes were positioned as shown in Appendix B. This provided for the movement of the digesting material first in one direction along the length of the digester, and then in the opposite direction for approximately the same distance, with a total path length of approximately twice the length of the digester. The dividing wall was provided with gaps at the top to enable the movement of gas to the gas outlet pipe (see below). The plant was constructed by CSIR personnel assisted by workers from the area, one of whom was a local builder who was employed to do the brickwork. A nylon net was fixed at the expected level of the slurry inside the digester. Its purpose was to cause a slight disturbance of the scum on top of the slurry when fresh material was added to the digester, and the slurry in the digester moved as a result.

The gas space inside the digester was painted with bitumen paint to reduce gas migration through the concrete and brick structures. Two manholes in the digester roof slab provide access to the digester and were closed with concrete covers. As the covers were not expected to be removed in the short-term, the manholes were sealed with plaster and covered with a bitumen sealant. The gas outlet pipe was fitted through the manhole cover adjacent to the digester inlet, together with a special inlet pipe for adding grass to the digester, which ended below the expected slurry level in the digester. The grass was to be pushed down with a plunger that would be used only for this purpose. The completed digester is shown in Figure C.3 in Appendix C.

Gas was to be collected in a separate gas holder that would regulate the gas pressure and thereby prevent a build-up of pressure inside the digester which could result in the formation of cracks along the angular joints in the gas storage space. Because of the relatively low cost and general availability of galvanised iron water tanks in rural areas, it was decided to test the suitability of this material for the storage of biogas. A gas holder was designed which comprised two galvanised iron water tanks which fitted into one another, both of which were to be covered with a rubber layer to provide additional protection against corrosion. The larger tank was to be filled with water which would be covered with a layer of oil on the outside to reduce evaporation. The other tank was to serve as gas collector, and would be held upright by means of a guiding system which was to consist of small wheels attached to the outer tank which would run along metal channels fixed to the inner tank.

Arrangements were made with a manufacturer of galvanised iron water tanks in Pretoria to build the gas holder according to these specifications. However, the gas holder was only delivered a few months after the date agreed upon, and was not manufactured to the specifications, e.g. features aimed at strengthening the tanks had not been added, the tanks were not covered with a rubber layer, and a different guiding system was provided. The gas holder was installed at the site, but did not function effectively. No payment was made for the gas holder, and it was decided to replace it once the rest of the system was operating satisfactorily.

A gas pipeline was laid to the homecraft centre approximately 100 m from the biogas plant, using 20 mm galvanised iron and polyethylene piping. Two water traps were provided along the pipeline where water had to be drained from the pipe. Gas valves were installed at three points in the gas pipeline, one of which was inside the homecraft centre, while the other two were placed at the gas holder and the digester respectively. A flame arrester was also installed in the gas pipeline at the homecraft centre. A fence was erected around the biogas plant and the power equipment (see Section 8.3.5), and safety signs indicating the presence of a flammable gas were placed on the fence and along the gas pipeline.

8.3.4 Construction costs of the biogas plant

A breakdown of the construction costs of the biogas plant at the school is provided in Table 8.4. The labour costs were estimated using the wage rates presented in Section 8.2.4, after which it was corrected for inflation by assuming an annual inflation rate of 15.3 % for 1991. However, higher wages had been paid during the construction of the plant. The costs related to the digging of the hole for the digester, as well as the changes which were made to the existing sanitation system, have not been included. The costs of the gas holder which are included, refer to the quoted figure from the manufacturer.

Table 8.4: Construction costs of the biogas plant at the Mzimhlophe Secondary School.

	Labour (1991 rand)	Materials (1991 rand)	Total (1991 rand)
Digester	870	2500	3370
Gas holder			1420
Piping and accessories	110	480	590
Total	980	4400	5380

8.3.5 Integration of the biogas plant and the sanitation system

Two boxes were built over the pipeline between the ablution block and the septic tank. The first box was to provide for the settling of the solids in the wastewater before it was pumped into the digester, while the second box was to enable the digester effluent to enter the pipeline to the septic tank (see below). The pipeline was cut in both boxes in such a way that it could be reconnected again if the system was not utilised.

A submersible sludge pump was installed in the settling box to pump the solids and some liquid to the digester inlet box, from where it would enter the digester. Effluent would then flow from the digester into an outlet box and along a pipe to the second box on the pipeline, from where it would flow to the septic tank. Two photo-voltaic panels were installed on the roof of a nearby classroom to charge a set of batteries. The pump was to be operated from the batteries by means of an inverter, as it had not been possible to find a sludge pump which could be operated directly from batteries. Difficulties were experienced with the selection of the inverter, as contradicting advice was given by various suppliers of solar equipment. The most critical factor was the ability of the inverter to provide the power required by the sludge pump during start-up. An inverter was finally purchased on condition that it was installed successfully. It was installed by the supplier, and required some adjustment for the specific load. The batteries and the inverter were placed in locked boxes on the site. Detailed descriptions of the sludge pump and all the power equipment are provided in Appendix F.

It was decided to operate the digester on human excreta for a few months before adding grass, to ensure that the basic system operated satisfactorily. There were some concern about the use of grass, as most of the grass was expected to remain inside the digester, which would require the emptying of the digester at regular intervals. In addition, grass which left the digester through the outlet pipe could possibly cause blockages in the pipes leading to the septic tank. The digester was initially filled with wastewater pumped from the septic tank at the school, which was very dilute. The digester then appeared to be leaking as the liquid level dropped during the following weeks. It was filled up once more by the tanker owned by the KwaNdebele Department of Works, which serviced the septic tank at the school (see Figure C.4 in Appendix C).

The operation of the system was discussed with the principal, homecraft teachers and school caretakers. The latter were to take responsibility for operating the pump and for adding grass to the digester, while the homecraft teachers would support them in these tasks. The continued cooperation of the homecraft teachers and the school caretakers was therefore crucial to ensure the success of the project. The sludge pump and the power equipment were installed in March 1992, and the caretakers were given instructions on the operation of the pump. They were to switch it on in the afternoons when all the pupils had left and the toilets were not used any longer. The pump would require less than two minutes to empty the settling pit, after which the caretakers had to switch off the pump. Arrangements were also made for the cutting and composting of grass by local women, and instructions were given to the caretakers on the composting of the grass.

8.3.6 Problems encountered

The pump operated well at first, but it jammed after a few weeks in operation. At an earlier stage it had been observed that a variety of solid objects found their way into the pipeline to the septic tank, including plastic bags and bottles. A rag was subsequently removed from the pump impeller, and it was decided to place a screen in the settling box to prevent large solid objects from entering the pump.

During May 1992 an attempt was made to steal the two batteries at the site, but this was prevented by the school caretakers. It was therefore decided to install a safe at the site in which the batteries would be kept. Storage in an office or classroom was not considered, as none of these had adequate security. In June 1992 the two solar panels installed on the roof were stolen, and to prevent further losses, the inverter and pump were removed from the site. These incidents were attributed to the fact that the security system at the school had been scaled down at the end of April 1992. The school is surrounded by a security fence, and until that time security guards had been on duty at the school at all times. However, this system was abolished by the KwaNdebele Department of Education, apparently due to a lack of funds. The matter was discussed with the school principal, who undertook to petition the department to reinstate the security guards at the school. However, as it seemed unlikely that the security situation at the school would improve again, some alternative means to enable the continuation of the project were investigated.

It was suggested by the Department of Mineral and Energy Affairs (DMEA) that greater involvement of the local community in the project should be sought to reduce the chances of equipment at the school being stolen. However, as the school was situated in a fairly large peri-urban area, it was virtually impossible to ensure the safety of the equipment by establishing a sense of community ownership of the biogas system. The employment of full-time security guards at the school had been necessary because of the problems with vandalism and theft in the past.

The possibility to operate the biogas plant on a batch-basis, i.e. to fill the digester with a new batch of wastewater every few months rather than adding fresh material every day, was investigated. An arrangement could have been made with the tanker which served the septic tank at the school to fill the digester each time the septic tank was emptied. This would have meant that the pump and the power equipment were no longer required at the school. However, the wastewater available from the tanker was extremely dilute and would not have produced significant quantities of gas, particularly as anaerobic digestion occurred in the septic tank. Moreover, this system would probably not have been viable in the long run, as it would have been dependent on the cooperation of the tanker operator.

Finally, the possibility of installing a security system at the biogas plant was investigated on request of the DMEA. Security measures which merely added to the difficulty of accessing the equipment would have been inadequate as there was no lighting at the school, and local people were unlikely to apprehend burglars even if they detected them. It would therefore have been necessary to install an electrical fence around the biogas plant and the power equipment, probably with an alarm attached. This would in turn have necessitated the installation of a platform to position the solar panels out of reach of any shadows cast by the fence and school buildings.

The cost of such a system was estimated as R 6500, of which approximately R 4200 was required for the electrical fence. In addition, further costs would be incurred by the CSIR to ensure that the biogas system was commissioned successfully and continued to operate satisfactorily. This option to provide for the continuation of the project therefore involved considerable expense. As the biogas system at the school had already cost considerably more than the amount budgeted for this purpose, it was not regarded as a viable option. The decision was therefore made to terminate this project.

8.3.7 Conclusions

The failure of the project at the school can be attributed to a combination of factors, which mainly relate to the complexity of the system that was installed, and the problems experienced with security at the school. However, the decision to implement biogas technology at a location such as a school, without prior experience in the use of human excreta and particularly the handling of the effluent, had been unfortunate. Ideally the first system of this nature should have been installed in a more controlled environment, where the nature of the risks involved could have been established and measures to handle the effluent could have been devised without risking the outbreak of disease at a public institution.

As the biogas plant never functioned normally, since problems had been encountered from the onset when the pump was installed, it had been impossible to evaluate the performance of this design. Very little benefit had therefore been derived from this project.

8.4 The experimental biogas plant

The third plant that was provided for in the project funded by the DMEA had an experimental function, i.e. the main aim was to study some aspects of the operation of biogas plants under local conditions. The objectives of the project were as follows:

- to monitor operational parameters which would assist in the sizing of biogas plants
- to test operational aspects related to different feed materials
- to demonstrate the technology to interested parties
- to test the chosen design and evaluate its performance
- to assess the economic viability of the design

8.4.1 Selection of the site

The following criteria were used to identify a suitable location for the plant:

- The plant had to be located in a neutral environment where design and operational aspects could be tested without negatively affecting the attitude of potential users to the technology.

- It had to be in close proximity to the CSIR as the plant would be monitored on a regular basis.
- Labour had to be available for the operation of the plant.
- Different types of feed materials had to be available for experimental purposes.

The Faculty of Agriculture at the University of Pretoria (UP) was approached as their experimental farm was seen as a suitable location for the plant. An agreement was subsequently reached with the head of the faculty on the matter. The UP undertook to provide a worker to operate the plant, while the CSIR would compensate them for the time spent by the worker on the project. The biogas plant would become the property of the UP once the project was completed. The site for the plant was selected in cooperation with professor G A Smith of the Department of Animal Sciences. The plant was to be located next to a broiler house where the use of the gas for heating purposes could be investigated in the future.

8.4.2 Design of the biogas plant

Although the main purpose of the experimental plant had been to study some aspects of the operation of biogas plants, it also provided the opportunity to test some aspects of the design of biogas plants. Two designs were considered for this plant, namely a tapered version of the floating-drum plant and a fixed-dome plant.

As discussed in Section 4.2, the floating-drum plant has a number of advantages, such as its ease of operation and utilisation, which would make it an attractive option in many instances, particularly if a gas drum was available that was less prone to corrosion than the mild steel drum. The installation of a floating-drum plant at the experimental farm would enable the testing of alternative designs for the gas drum made of different materials. Moreover, the floating gas drum would provide a fairly simple way to measure gas production, which would form an essential part of the monitoring of the plant. In addition, this would provide the opportunity to develop a floating-drum plant that could be built to sizes greater than 10 m^3 (see Section 4.2.2). It was therefore decided to retain the focus on the floating-drum plant during the study, as most benefit could be derived in this way, rather than attempting to build a fixed-dome plant.

8.4.3 Installation of the plant

The plant that was installed at the experimental farm is shown in Figure C.5 in Appendix C. It comprises a tapered brick digester and a gas drum that was made by modifying an asbestos cement water tank. A detailed discussion of the design was presented in Section 4.2. The plant was built in October 1991 by a small builder who was subcontracted by the CSIR.

The digester was filled with a mixture of water and cattle dung which had been dug from a grazing area at the experimental farm. It is preferable to use fresh manure for the filling of a plant, but it was argued that practical considerations would often dictate the use of that which was available. In many cases dry dung, e.g. from kraal floors, would be available to the owners of biogas plants in larger quantities than fresh manure. It was therefore decided to fill the digester with the dung from the grazing area to establish whether this would result in any serious operational difficulties.

Gas production started within a few weeks and, after a waiting period to enable the bacterial population to establish itself, the daily feeding of the plant commenced. Fresh manure was collected from the dairy at the farm on a daily basis and mixed with water before it was allowed to enter the digester.

8.4.4 Problems encountered

During the second month of the operation of the plant it became evident that the vertical movement of the drum was being restricted by a thick scum which had formed on the slurry. Indications were that plant matter in the dung as well as pieces of dry dung which tended to float on the slurry, had resulted in heavy scum formation. The manager of the experimental farm, Mr Roelf Coertze, confirmed that the dung that was used to fill the digester probably contained hay cuttings which are usually fed to the cattle.

Several attempts were made to dilute the slurry and to break the scum, but the problem could not be resolved. The gas drum was gradually lifted out of the slurry by the solid layer of material which formed on top of the slurry. Some scum formation had been expected in the plant, but the situation which developed was far beyond expectations. The design of the outlet of the digester, i.e. in the form of an overflow rather than an outlet pipe (see Section 4.2.10), also contributed to this situation, as the solid scum prevented slurry inside the digester from leaving the digester via the overflow. When the gas drum was removed from the digester, the solid layer on top of the slurry was strong enough to support the weight of a grown person. The digester was emptied partially to remove most of the material that could lead to scum formation, and an arrangement was made with the plant operator to refill the plant by adding fresh manure on a daily basis. When this proved to be too time-consuming, the digester was refilled with fresh manure that was obtained from an abattoir in July 1992. No serious scum formation was experienced during the remainder of the project. This experience clearly indicated that the dung which was obtained from the grazing area of the cattle, was not suitable for use in a biogas digester.

The gas drum was slightly modified at this time, which included the attachment of handles to provide for the easier installation and removal of the drum. After the drum had been installed once more, it was found to be riddled with gas leaks which could not be repaired, as discussed in Section 4.2.7. It was therefore decided to discard the asbestos cement drum, and to investigate the use of a gas drum that was made from a different type of material.

A UV-stabilised high-density polyethylene (HDPE) drum was subsequently purchased and modified for use as a gas drum (see Section 4.2.8). However, problems were experienced with the guiding of the drum, as the external guide system had been designed for a drum made of a rigid material. Various modifications were made to the guide system, and finally to the drum itself, until a system was found which operated satisfactorily. This process was discussed in detail in Section 4.2. The biogas plant which had been modified successfully, is shown in Figure C.6 in Appendix C, and design drawings of the HDPE gas drum and the tapered brick digester are provided in Appendix B.

The final changes to the gas drum and the guide system were made in the middle of December 1992. In the week that followed the gas was used to conduct tests on locally available gas burners (see Figure C.8 in Appendix C) to establish the modifications that were required to ensure proper functioning of these burners using biogas, as well as the gas consumptions rates involved. The results have been discussed briefly in Section 5.2. Unfortunately the feeding of the plant was discontinued in January 1993 due to a severe shortage of labour at the experimental farm. The matter was discussed with the head of the Faculty of Agriculture at the UP, Professor Johan Van Zyl, who undertook to explore possible ways in which the plant could be utilised by the university for research and demonstration purposes.

8.4.5 Construction costs of the plant

A breakdown of the construction costs of the biogas plant is provided in Table 8.5. The costs of the external guide system for the asbestos cement drum were included in the digester costs. The cost of the gas drum had to be estimated as only half of the water tank was used for this purpose (see Section 4.2.7). Therefore only 75 % of the costs of the asbestos cement water tank was included in the costs of the gas drum. The labour costs were estimated by using the wage rates provided in Section 8.2.4, although higher wages were paid during the construction of the plant. It was corrected for inflation by assuming an annual inflation rate of 15.3 % for 1991. The cost of the labour required for the digging of the hole for the digester was not included.

Table 8.5: Construction costs of the experimental biogas plant at the University of Pretoria.

	Labour (1991 rand)	Materials (1991 rand)	Total (1991 rand)
Digester	570	1690	2260
Gas drum	50	1170	1220
Piping and accessories	30	400	430
Total	650	3260	3910

The costs of the biogas plant with the modified HDPE gas drum and the external guide system described in Section 4.2.8, have also been estimated. The costs of the HDPE gas drum and the new guide system for the drum were R 1060 (1992 rand), while the digester would have cost R 2130 (1991 rand) if the initial external guide system had not been installed. The total costs of the plant were therefore approximately R 3050 (1991 rand) without the gas pipes and accessories. This is somewhat lower than the total cost of the original unit shown in Table 8.5.

8.4.6 Monitoring of the plant

The intention had been to monitor the experimental plant closely with regard to temperature, feeding rate, slurry concentration and gas production, to obtain some data which could be used for the sizing of plants built locally. However, because of the difficulties experienced with the system which were discussed in Section 8.4.4, the plant was operated normally only from August 1992, while gas production measurements could only be conducted from the middle of December 1992. As the feeding of the plant was discontinued in January 1993 due to labour shortages at the farm, it has not been possible to monitor the gas production from the plant in any meaningful way.

8.4.6.1 Manure and slurry composition

Samples of the fresh dung which were collected at the dairy on the experimental farm, the slurry inside the digester, and the effluent from the plant, were taken at irregular intervals. A specially made sampler was used to obtain samples from the inside of the digester. The samples were analyzed in terms of total solids and volatile solids content as well as COD, and the results are presented in Table 8.6. One set of samples was analyzed during each month indicated in the table.

Table 8.6: Results of laboratory analyses of manure and slurry samples obtained from the dairy and digester at the experimental farm of the University of Pretoria.

Sample	Date	COD (g/ℓ)	Total solids	Volatile Solids	VS as % of TS
Fresh dung collected from dairy	January 1992	-	23.6 %	-	-
	August 1992	103	182 g/ℓ	170 g/ℓ	93
	October 1992	177	22 %	18 %	-
Slurry inside digester	September 1992	39	43 g/ℓ	35 g/ℓ	81
	January 1993	42	56 g/ℓ	46 g/ℓ	82
Effluent collected from overflow	January 1993	19	18 g/ℓ	13 g/ℓ	72

The TS content of the slurry in the digester appeared to be fairly low, which could be attributed in part to some stratification inside the digester. The TS content of the effluent seemed to be considerably lower than that of the slurry in the digester, which could be attributed to the location of the outlet (i.e. an overflow). This could be compared with the findings in the case of the Mathabela family plant, which was equipped with an outlet pipe rather than an overflow. As discussed in Section 8.2.5, the TS content of the effluent from the latter seemed to be slightly higher than that of the digester content.

8.4.6.2 Digester and ambient temperature

The digester temperature and the ambient temperature at the site[26] were monitored during part of the project, by means of thermocouples which were connected to a datalogger[27]. The range of temperatures that were recorded each month, as well as the average temperature for the month, are presented in Table 8.7. No measurements were obtained in December 1992 and January 1993 as difficulties were experienced with the measuring system which took some time to resolve.

Table 8.7: Mean digester and ambient temperatures recorded at the experimental plant at the University of Pretoria.

Month	Digester temperature (°C)		Ambient temperature (°C)	
	Average	Range	Average	Range
June 1992	15	12-17	8	-3-22
July 1992	15	12-18	11	-1-26
August 1992	17	14-18	13	9-18
September 1992	18	16-20	21	12-32
October 1992	22	19-26	22	12-34
November 1992	19	18-22	18	12-31
December 1992	-	-	-	-
January 1993	-	-	-	-
February 1993	17	16-19	19	13-31

[26]No attempt was made to record ground temperatures, as the aim was to relate the digester temperature to the ambient temperature, which could be measured fairly easily by users of the technology.

[27]According to Dr T B Scheffler of the University of Pretoria the use of thermocouples to measure the ambient and digester temperatures had not been appropriate, as thermocouples are best suited to measuring higher temperatures as well as temperature differences. He suggested that the use of integrated circuit temperature sensors would have been more appropriate at the relatively low temperatures involved, as these provide significantly better signal-to-noise ratios as well as accuracies compared to thermocouples. (Personal communication with Dr Scheffler in August 1994.)

The digester temperature remained fairly low during the period involved, with the highest average temperature recorded being 22 °C in October 1992. Digester temperatures in November 1992 and February 1993 were lower than expected, which could be attributed to the relatively low ambient temperatures that were recorded during these months. The latter were considerably lower than the long-term mean ambient temperatures for Pretoria during these months (approximately 20.5 ° and 21 ° respectively) which have been reported by Schulze (1986) (see Appendix E). For most of the period involved the digester temperature remained below 20 °C, indicating that relatively low gas production rates would have been achieved in the plant, as discussed in Section 3.3.2. During winter the average digester temperature remained higher than the average ambient temperature, while no clear trend could be identified during warmer months.

8.4.7 Conclusions

The installation of the plant at the experimental farm provided for the development of an alternative gas drum to the mild steel drum, which would reduce the costs of the floating-drum plant, as discussed in Section 4.6. In addition, the tapered brick digester which would be suitable for larger plant sizes have been tested, and various aspects of the design of floating-drum plants have been evaluated (see Section 4.2). Extensive monitoring of the system had not been possible because of the problems which had been experienced.

8.5 The pilot plant for large-scale applications

The fourth plant that was built as part of the DMEA project was a pilot-plant for the production of biogas on a large scale. The main aim was to develop a low-cost design which would be suitable for large-scale applications. As the flexible cover biogas plant is the only design considered in this study which is suitable for this purpose, the project focused specifically on this design. The objectives of the project were as follows:

- to develop suitable techniques for the construction of the digester of the flexible cover plant
- to evaluate the suitability of different materials for the gas holder of the flexible cover plant
- to test the design and evaluate its performance
- to assess the economic viability of the design
- to demonstrate the technology to interested farmers as well as to farmworker households

8.5.1 Selection of the site

The pilot plant had to be built at a commercial farm where it could serve as a demonstration unit to interested farmers. It was decided to build the plant as close as possible to Pretoria, as experience had shown that the CSIR needed to be closely involved in the construction and commissioning of these plants, while longer distances resulted in considerable increases in the costs and the difficulties associated with the installation of a plant (e.g. the biogas system that was installed at a school in KwaNdebele).

The possibility of using a substrate such as pig manure or chicken excreta was investigated, as cattle manure was already used in the Mathabela family plant as well as the experimental plant at the University of Pretoria. Because of the greater operational difficulties associated with the use of chicken excreta in biogas plants (Hobson *et al* 1980: 248) (Werner *et al* 1989: 22), it was decided to locate the plant at a piggery. Contact was established with three farmers in the vicinity of Pretoria who owned piggeries, through organisations such as the Rural Foundation and the South African Agricultural Union. All the piggeries were equipped with extensive waste disposal systems which utilised water to flush the animal houses. An important consideration was therefore the ease with which existing arrangements for waste disposal could be modified to divert some of the wastewater into a biogas plant.

The farm Donkerhoek was finally selected, which is owned by Mr Gerhard Braak (Sr), and is situated east of Pretoria (see Appendix A). The waste disposal system at the farm comprises a network of open concrete channels along which the wastewater from the pig houses flows to open ponds where the solids are allowed to settle. The flow of the wastewater is aided by a natural gradient between the pig houses and the settling ponds. The possibility of using the gas at the farm was discussed with the owner, who suggested that it could be piped to a rondavel approximately 80 m from the plant, where meals were prepared for the farm labourers during the day.

8.5.2 Installation of the plant

The plant, which is shown in Figure C.9 in Appendix C, comprised a ferrocement digester covered with a balloon-like plastic gas holder. The design and construction of the plant were discussed in some depth in Section 4.4, and design drawings are provided in Appendix B. It was built in March 1992 by CSIR personnel assisted by casual labourers.

The biogas plant is located next to a point of convergence between the two main channels along which wastewater from the pig houses flows to the settling ponds a short distance away (see design drawings in Appendix B). It is therefore possible to utilise the wastewater from either or both of the channels for the feeding of the digester. The height of the walls of the existing concrete channels were slightly increased at the junction, and an inlet chamber was built adjacent to one of the channels. A sluice gate was installed between the channels and the inlet chamber of the biogas plant to enable the diversion of the wastewater, which enters the plant when the sluice gates to the settling ponds are closed and the sluice gate to the biogas plant is opened.

The digester was filled with wastewater from the piggery, to which a bakkie-load of fresh cattle manure was added to accelerate the starting-up process. Cattle manure was a suitable seeding agent in this case as it contains the bacteria required for anaerobic digestion in larger quantities than pig manure (Fulford 1988: 34). Because of the danger of acidification during the starting-up of a digester utilising pig manure (Werner *et al* 1989: 23), and the fact that it was winter and therefore cold at the time, no more wastewater was added to the plant for ten weeks to enable the bacterial population to become established. Biogas production started during this period.

8.5.3 Problems encountered

Arrangements were made with the farm manager for the feeding of the plant once a day when the pig houses were flushed with water, as the wastewater contained most solids at that time. However, the plant was not fed an a regular basis, probably as no provision had been made for the utilisation of the gas at the time (see below). In November 1992 the gas holder developed a few punctures without any apparent reason, which raised questions regarding the suitability of the material which had been used for the gas holder. It was subsequently replaced by a gas holder manufactured of PVC Elvaloy, which has some resistance to mechanical damage, in addition to being UV-stabilised (see Section 4.4).

As the gas pressure in the gas holder was insufficient to enable the piping of the gas to the cooking area, weights were installed on it in December 1992 to provide a gas pressure of approximately 10 cm water pressure at the plant (see Figure C.10 in Appendix C). However, the pressure in the gas holder did not increase beyond about 3-4 cm water pressure after the weights had been installed. This matter could not be resolved, and as a result no gas pipeline was installed at the plant. It should be noted that this design is mainly intended for large-scale applications, which would mean that the gas could be used in engines because of the relatively large quantities of gas which would be produced. In such cases a low gas pressure would be sufficient as the gas would be sucked into the carburettor of an engine. Alternatively the gas could be drawn from the plant by means of a suction fan.

8.5.4 Construction costs of the plant

A breakdown of the construction costs of the biogas plant with the original gas holder is presented in Table 8.8. The labour costs have been estimated using the wage rates presented in Section 8.2.4, although higher wages had been paid during the construction of the plant. The labour required for the digging of the hole for the digester has not been included. The cost of the PVC Elvaloy gas holder was R 650 (1992), which was higher than the cost of the original gas holder, but it was expected to have a much longer lifetime (i.e. in excess of ten years).

Table 8.8: Construction costs of the pilot plant at the piggery in Donkerhoek.

	Labour (1992 rand)	Materials (1992 rand)	Total (1992 rand)
Digester	510	1420	1930
Gas holder	140	140	280
Piping and accessories	30	40	70
Total	680	1600	2280

8.5.5 Monitoring of the plant

Two samples were taken of the wastewater which entered the biogas plant, and one of the effluent from the plant. The samples were analyzed in terms of total solids and volatile solids content as well as COD, and the results are presented in Table 8.9. In addition, the ammonia-nitrogen content and the alkalinity of the samples were determined, although no danger of ammonia toxicity had been expected as the wastewater which entered the plant was extremely dilute (of the order of 1 % TS).

Table 8.9: Results of laboratory analyses of samples obtained from the digester inlet and effluent at the commercial piggery.

	Inlet	Effluent
COD (g/ℓ)	17	12
Total solids (g/ℓ)	12 (two samples)	5.6
Volatile solids (g/ℓ)	9.6	4.8
pH	7.2	7.4
Alkalinity (mg/ℓ $CaCO_3$)	5150	6375
Ammonia-nitrogen (mg/ℓ)	920-1250 (two samples)	1635

8.5.6 Conclusions

The installation of the plant at the piggery provided for the development of a low-cost plant of the flexible cover design which should be suitable for application on a large scale. As discussed in Section 4.6, this plant provides for the lowest energy costs of biogas of all the plants that were developed during this study.

8.6 The ferrocement fixed-dome plant

The fifth plant that was built as part of this study was a fixed-dome plant, the design and installation of which were funded by the CSIR. The main aim of the project was to develop a fixed-dome design which could be built locally without the need for highly specialised skills as in the case of the brick digester (see Section 4.3). In addition, the feasibility of connecting a toilet to a biogas plant which is mainly operated on animal manure, was to be investigated. The specific objectives of the project were as follows:

- to develop suitable techniques for the construction of a ferrocement fixed-dome digester
- to test the design and evaluate its performance
- to assess the economic viability of the design
- to assess the health risks posed by the human excreta from a single toilet connected to a biogas plant
- to investigate the operational complexities arising from linking a toilet with a biogas plant
- to demonstrate the technology to smallholders and farmworker households
- to assess the social acceptability of the technology among these people

8.6.1 Selection of the site

During the course of the project funded by the DMEA, a large number of enquiries were received from the owners of smallholdings in the vicinity of cities and towns, expressing an interest in biogas technology. Indications were therefore that smallholders constituted an important group of potential recipients of the technology, and for this reason it was decided to build this biogas plant on a smallholding close to Pretoria.

A small dairy which is situated close to the Rietvlei dam south of Pretoria (see Appendix A) was found to be suitable for this purpose. Manure was available from ± 24 cattle that were kept in an enclosure. The gas was to be used by the five labourers who were employed at the dairy, who used firewood for cooking purposes. The owners of the Doringkloof dairy, Mr and Mrs Fouchee, were in the process of planning the housing of the labourers and no sanitation facilities had yet been provided. This provided an ideal opportunity for the incorporation of a toilet as part of the system.

An agreement was reached with the owners of the dairy regarding their participation in the project. The experimental nature of the project and the consequent risks involved, were explained to them. A suitable site for the plant was selected adjacent to the planned houses of the labourers as well as a planned enclosure for the cattle.

8.6.2 Installation of the plant

A small builder was subcontracted to build the plant under supervision of the CSIR. Although the builder had rendered satisfactory service to the CSIR on previous occasions, difficulties were experienced during this project. Most of the construction was therefore done by CSIR staff, who were assisted by casual labourers. The design and construction of the plant have been discussed in some depth in Section 4.3.2, and design drawings are provided in Appendix B. The completed digester is shown in Figure C.11 in Appendix C. The plant was filled with a mixture of manure and water just before the conclusion of this study. When the digester had been filled completely, the concrete manhole cover was set into the manhole on top of the digester and sealed with a bitumen sealant.

8.6.3 Construction costs of the plant

A breakdown of the construction costs of the plant is given in Table 8.10. The labour costs have been estimated using the wage rates that were presented in Section 8.2.4. The costs of the labour required for the digging of the hole for the digester have not been included.

Table 8.10: Construction costs of the ferrocement fixed-dome biogas plant.

	Labour (1992 rand)	Materials (1992 rand)	Total (1992 rand)
Digester	1390	2000	3390
Piping and accessories	30	100	130
Total	1420	2100	3520

8.6.4 Conclusions

The installation of the plant at the dairy has provided for the development of a ferrocement fixed-dome plant which would appear to be a viable alternative to the brick fixed-dome plant, without the high risks of failure which are associated with the latter because of cracks which may form in the dome. As discussed in Section 4.6, this plant provides for the lowest energy costs of biogas of the small-scale plants that were developed during this study.

CHAPTER 9
UTILISATION OF BIOGAS TECHNOLOGY BY SMALLHOLDERS

9.1 Introduction

The technical requirements for the utilisation of biogas technology by smallholders were considered in Chapter 6. In this chapter particular attention will be given to socio-economic matters related to the utilisation of the technology by smallholders. Some responses of people in the former homelands to the technology will be considered, and the experience of the Mathabela family will be discussed in great depth. Finally, an attempt will be made to establish the socio-economic characteristics of the group among smallholders in the former homelands and newly established small farmers in South Africa (see Section 2.2), that would be able to utilise the technology successfully.

9.2 Socio-economic matters related to the utilisation of biogas technology

Some socio-economic factors which have had an impact on the adoption of biogas technology, as well as consequences of the introduction of the technology, are considered in this section, based on experiences in countries like India and Tanzania. As this study mainly focused on the development of the technology, with relatively little opportunity for the socio-economic evaluation of the technology, the matter is dealt with fairly superficially.

In general the attitude of potential users to biogas technology will be influenced by their exposure to existing biogas systems. Disappointing experiences with biogas plants, for example low gas production as a result of manure shortages, have been found to inhibit the further adoption of the technology in an area (Kijne 1984: 65). On the other hand, the social prestige associated with a biogas plant has been an important consideration for households who have adopted the technology in Tanzania (Kellner 1991a: 8) as well as in India (Kijne 1984: 50).

Different user groups respond differently to biogas technology because of their particular needs and priorities. Based on field experience in India, Kijne (1984: 60) has made an assessment of the relative importance of different considerations regarding the technology among men and women from poorer and more affluent rural households respectively, which is presented in Table 9.1. Some of these factors will be discussed below.

Table 9.1: **Estimated importance of considerations regarding the adoption of biogas technology for different socio-economic groups and men and women. (Kijne 1984: 61)**

	TARGET GROUPS			
	Rich		Poor	
	men	woman	man	woman
1. Financial (cash flow)				
credit acquirement	o	-	+	o
loan repayment schedule	o	-	+	o
savings on fuel expenditures	+	o	+	+
sale of saved fuel	o	-	+	+
crop sales	+	o	o	0
2. Comfort				
quicker cooking	-	+	-	o
no smoke	o	+	o	+
clean kitchen/utensils	o	+	o	+
reduced fuel collection	-	-	o	+
standing cooking	o	+	-	o
3. Labour/time				
increased leisure	o	+	o	o
extra prod. labour	-	-	+	o
reduced fuel collection	-	-	+	+
cleaning kitchen utensils	-	o	o	+
more attention for children	-	o	o	+
4. Fertilizer				
better quality	o	-	+	o
higher quantity	+	-	o	-
5. Education				
more time for education child.	-	-	o	o
6. Health				
no smoke eyes/lungs	-	o	-	+
7. Political/social status				
support nat.dev.plan	+	o	-	-
more status in group	+	+	o	-
more contact with outside world	+	+	o	-
8. Deforestation				
reduction nat. deforestation	-	-	-	-

-	=	no interest
o	=	neutral
+	=	interest

9.2.1 Activities of households

The introduction of biogas technology generally have an impact on the activities of the households involved (Kijne 1984: 48). The time required for tasks such as the collection of cooking fuels, e.g. firewood, for the cooking process itself, and for the cleaning of utensils, may be reduced (Kijne 1984: 48). However, tasks such as the collection of water and manure for the plant, the feeding of the plant, the disposal of the digested slurry and the maintenance of the plant would require additional labour. In areas where the regular fertilising of fields had not been implemented before, the additional work-load which would result from this practice could be significant (*ibid*).

In India it has been found that the impact on the activities of households differs for poorer and more affluent households (Kijne 1984: 48). In the case of more affluent households the additional labour demands for the operation and maintenance of biogas plants appear to be insignificant compared to the time savings which result from the use of biogas (*ibid*). Reasons for this include the fact that these households often employ labourers to feed the biogas plants, and often have access to convenient water supplies (*ibid*). Poorer families, on the other hand, have greater difficulties in obtaining sufficient quantities of dung and water, and have to meet the additional labour demands themselves. As a result, the net time savings which may result from the introduction of biogas plants tend to be less noticeable (kijne 1984: 50).

According to Kijne (1984: 51) the gender division of labour within households is often altered by the introduction of biogas technology. It has been found that men generally take responsibility for the additional tasks related to biogas plants, while the time savings which result from the use of biogas mostly affect women (*ibid*). Kijne (1984: 51) points out that such a redistribution of work would seem appropriate in the light of the existing unequal division of labour between men and women, and the work-load of poor rural women in particular. However, the introduction of biogas technology could also result in increased demands on women's time, e.g. for the collection of water to feed the plant. The effect of the introduction of biogas technology on the work-load of individual household members, and women in particular, therefore needs to be considered, rather than its effect on the household as a whole (*ibid*).

In Tanzania the reduction in the work-load of households as a result of the installation of biogas plants is seen as an important factor which has contributed to the acceptability of the technology (Neumann 1990: 1). The first priority among both men and women in households who own biogas plants, has been the replacement of firewood with biogas. As firewood is generally collected, the use of biogas has lead to a reduction in the time required for household chores of seven hours per week on average (*ibid*). In order to ensure that these benefits outweigh the additional labour required for the feeding of the plant, biogas plants are installed as part of a unit which includes a stable with a concrete floor that is directly connected to the mixing box of the plant (Kellner 1991a: 5).

9.2.2 Uses of the technology

The differences between the responses of men and women to biogas technology can be related to their specific responsibilities in the household, which determine their needs and priorities. Women often give priority to the use of biogas for cooking (Kellner 1991b: 34), as benefits such as the resulting savings in time and labour are mainly of concern to them. Other benefits which are of importance to women include the following:

- Improved conditions in the kitchen, because of reduced smoke and greater cleanliness compared to woodfires leading to improvements in health (Kijne 1984: 50).

- Improved convenience, such as the quick preparation of small quantities of food (Kellner and Lwakabamba 1985: 318) and cooking in an upright position (Kijne 1984: 50).

- Improved safety of fuel use (Kellner 1991a: 8), leading to fewer burning accidents, particularly with small children (Kijne 1984: 51).

According to Kijne (1984: 50) changes in cooking practices as a result of the introduction of biogas, seem to have occurred faster than had been expected in the light of the deep-rooted nature of traditional cooking practices in India:

> Very few women reveal any problems related to the change to gas cooking, such as the taste of the food, the fact that not all dishes can be cooked on biogas or not all pan sizes used, or problems of heat control and 'tending' of the gas fire (*ibid*).

In contrast with the priorities of women, men often favour the use of biogas for lighting purposes (Kellner 1991b: 34), as well as for "productive" activities, e.g. to power irrigation pumps or chaff cutters (Kijne 1984: 62). They also tend to regard the production of fertiliser as the most important product from a biogas plant. Men from wealthier households tend to be more concerned about larger quantities of fertiliser, as they own larger pieces of land compared to poorer households, where the quality of fertiliser is of greater concern (*ibid*). Women in Tanzania have also shown considerable interest in the use of slurry as fertiliser, apparently because they are responsible for vegetable and fruit production near the house where the slurry can best be utilised (Neumann 1990: 2).

It has been found that households who adopt biogas technology do not necessarily change to the exclusive use of biogas as energy source. In Tanzania traditional meals are still cooked on a fire for which wood is collected, although wood use is reduced by the installation of a biogas plant (Neumann 1990: 2). Kerosene lamps are used in addition to biogas lamps, presumably because of their mobility, but kerosene use is also reduced (*ibid*). Charcoal is still used for specific purposes such as the roasting of maize and meat or for heating. According to Kijne (1984: 15) woodfires or dried dung may still be preferred in India for long and slow cooking.

9.3 Preliminary studies on the acceptability of biogas technology

Before the installation of the biogas plant at the Mathabela homestead, an energy study had been conducted by Kennedy (1990) in the village of Cottondale, which is situated close to Timbavati where the Mathabela family lives (see Section 8.2.1). The questionnaire included a few questions on biogas, which were mainly of a simple nature as the technology was not familiar to the respondents. The results were analyzed by Trace (1990), and he reported that 46 % of the respondents "liked the idea of biogas a lot", while 30 % "liked it a little" and 12 % "disliked it a lot". In addition, 84 % of respondents did not perceive the feeding of a biogas plant as a problem. One respondent was of the opinion that the technology was not advanced enough (Trace 1990). The positive responses to the technology that were reported, include the following (Trace 1990):

- It can be used for cooking and lighting.
- It provides an energy option where electricity is not available.
- There is no need for collecting wood.
- It is an alternative to paraffin.
- It is an easy way to cook.
- It will save money.
- It can be used for all household purposes ("works everything in the house").
- It can replace all other fuels ("won't need any other fuels").
- There is no need to pay for it.

A significant number of respondents observed that biogas could be used for all household purposes, but no information was obtained on the purposes envisaged by these respondents. The final comment seems to indicate that the respondent did not understand that the construction of a biogas plant would require a significant investment. A number of respondents had reservations because the technology was strange to them (Trace 1990).

In June 1991, after the biogas unit at the Mathabela family had been in operation for six months, 77 households in the villages of Timbavati and Cottondale who had visited the biogas plant, were interviewed to assess their response to the technology[28]. The households did not form a representative sample of any particular community. The household income distribution was similar to that reported by Kennedy (1990: 50) for the village of Cottondale, with slightly more households in the lower income groups. An important difference was that only 51 % of the respondents in the biogas study owned livestock, compared to the 84 % of households in Cottondale (Trace 1990: 12). The most important findings were the following:

- 4 % of respondents stated that they would not consider the use of biogas.
- 80 % of respondents did not perceive the labour and time required for the feeding of the plant as being a problem.
- The use of communal digesters were unacceptable to 56 % of respondents, the main reason being the possibility of clashes between neighbours.

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[28]The study was conducted by Baby Mogane-Ramahotswa of WATERTEK (CSIR).

- Those respondents prepared to use communal plants would mostly prefer to share a plant with only one other family.
- 66 % of respondents were opposed to the use of human excreta in biogas plants, with younger people (15-34 years) being more receptive to the idea, while some older people responded that they "would rather starve than accept food prepared on gas produced from human excreta".
- Respondents would generally prefer to pay for a biogas plant in monthly instalments rather than in a lump sum.
- Some respondents preferred biogas to electricity as it involves a single large payment rather than continued monthly payments.
- 43 % of respondents stated that they would pay any amount required for a biogas plant, while the others gave estimates of what they would be able to afford, ranging between R 30 and R 2400 (average R 790).

The following comments of a positive nature were made during this study:

- The main expenditure is a once-off payment which is not the case with electricity.
- It is less expensive than other fuels (LPG, paraffin, coal, electricity).
- It is an investment for a lifetime.
- It will reduce the time needed to fetch wood.
- It involves no operational costs.
- The time and labour spent on collecting dung is preferable to spending money on fuels.
- It will prevent air pollution (smoke from woodfire) and environmental degradation (chopping down trees).
- Communal plants can benefit many people.
- The slurry can be used as fertiliser.
- The maintenance of the plant is simple.
- Dung can be collected from the kraals of neighbours, the open veld and dipping troughs.

Generally the comments made during this study showed that respondents were more informed about the technology, as a result of their exposure to the plant at the Mathabela family. However, the final comment again reflected some unrealistic ideas, which were expressed by a significant number of respondents. The respondents involved in the surveys as well as other people in the area who had seen the biogas plant, often did not seem to understand the implications of installing a biogas plant, such as the quantity of waste that would be required on a daily basis, the cost of a plant, and the maintenance that would be required. A number of requests had been received from households in the area for assistance with the construction of biogas plants. However, most of them did not have access to sufficient waste to run a biogas plant. The reasons that were given for a negative response to the technology in both the surveys, namely a scarcity of water and dung, the high costs of a biogas plant, and the dangers associated with the utilisation of gas, reflected a greater realism in the assessment of the technology.

These studies have clearly been of limited value, as most of the respondents would be unable to utilise the technology, while the results do not reflect the decisions that people would make if presented with the opportunity to install biogas units at their own expense. However, it has provided some indication of the response of people in the area to the technology.

9.4 The Mathabela family: A case study

In this section the impact on the Mathabela family as a result of the introduction of biogas technology, and their experience of the technology, will be discussed in great depth. This experience has provided some valuable insights regarding the requirements for the successful utilisation of the technology by smallholders in the former homelands and elsewhere (see Section 2.2). The circumstances of the family and their experience of biogas technology were assessed in various ways:

- Trace (1990: 8) conducted an interview with a member of the family in 1990 before the plant was installed.
- Baby Mogane-Ramahotswa of the CSIR conducted interviews with family members in July 1991.
- Douglas Banks of the WRF had numerous informal discussions with family members and interviewed some family members in December 1991.
- The author interviewed some family members in October 1992.
- CSIR personnel, including the author, conducted informal discussions with family members at different times.

The circumstances of the family changed somewhat between the installation of the biogas plant and the end of this study, as will be discussed below. Together with the natural dynamics within the family, this resulted in a lot of variation in the way that the biogas plant was operated and used.

9.4.1 Composition and income of the Mathabela family

The composition of the family seemed to have changed somewhat during the project period. In 1990 the family comprised six adults and three children under the age of 18 who all had their meals at the homestead (Trace 1990). However, during most of the period under consideration, the household comprised Mr and Mrs Mathabela, one adult son, Freddy, two teenage sons, Herbert and Bernard, and a young teenage daughter, Tinyeko. During 1992 Freddy was married to Marie Antoinette, who subsequently joined the household together with their small child.

At the time that the plant was installed, the family's only formal income was R 200 per month (Trace 1990), which was earned by Mr Mathabela who worked at a nearby school as a caretaker and night watchman. Subsequent to the installation of the digester Freddy started working regularly for the Wits Rural Facility (WRF) as an interpreter and field assistant, and by mid-1992 their combined income was about R 1000 per month. No other members of the household had significant sources of income. In October 1992 it was found that

Mr Mathabela, who earned R 500 per month at the time, was still the only regular contributor to the combined household income.

9.4.2 Livestock keeping practices

The Mathabela family's cattle graze on communal land during the day and usually return to the kraal at the homestead for the night. The number of full-grown cattle owned by the family varied between eight and nine, while one or two calves were also noted during most of 1991. In October 1992 it was noted that the family's remaining eight head of cattle were in a poor condition due to the severe and prolonged drought in the area.

In December 1991 it was established that a young teenage boy, Mdludi, who lived close to the Mathabela family, was paid R 30 per month to herd the cattle during the day and to feed the biogas plant. At times these tasks were performed by other young boys, while the cattle were sometimes left unherded during the day, e.g. in October 1992. Mention was often made by the family of the straying of the cattle, i.e. when they failed to return to the kraal at night. In October 1992 this seemed to happen as often as once or twice per week, probably because they were not herded at the time.

9.4.3 Feeding of the biogas plant

The feeding procedure involves the collection of fresh dung from the kraal, which is about 10 m from the biogas plant, and the mixing of the dung with water in the mixing box before allowing it to flow into the digester. The feeding of the plant is made somewhat awkward by the height of the mixing box (see Section 8.2.3), but family members did not seem to perceive the feeding of the plant as cumbersome. According to family members the digester was fed every day, except when their cattle did not return to the kraal at night or when water was unavailable. Observations by Douglas Banks seemed to indicate that this happened fairly frequently. Generally the fresh dung that was not collected on a daily basis would be lost to the system, as it would have dried out and hardened in the sun, and would be trampled into the ground by the cattle. This problem could have been avoided if the dung was collected every day and stored in a covered container.

In June 1991 family members indicated that Mr and Mrs Mathabela were responsible for the feeding of the plant during the week, while the boys in the family fed the plant over weekends and during school holidays. Although there was no specific time at which feeding took place, it was mostly done in the mornings. In December 1991 the situation was somewhat different, in that young teenage boys were paid to herd the cattle and to feed the plant, which they did either in the morning or at lunch time. Generally feeding practices have varied considerably during the period under consideration. Men were predominantly involved in the feeding of the digester, although Mrs Mathabela also fed it on occasion.

As the quantity of dung available for the feeding of the digester was inadequate, some measures to improve the situation were considered. The possibility of providing the kraal with a concrete floor was suggested to the family. At first they appeared to react positively to the idea, agreeing that dung collection would be improved by this measure. However, at a later stage they expressed concern about the possibility that the cattle might experience discomfort (e.g. cold). A further consideration was the fact that they were planning to move the cattle kraal at some stage. Another possibility that was considered to increase the feeding rate of the digester, was the collection of dung from the cattle kraals belonging to relatives or friends on a regular basis. This had been done occasionally, mainly for specific purposes such as the refilling of the plant after the installation of the gas deflecting ledge (see Section 4.2.1). However, family members indicated that attempts to collect dung on a more regular basis would be met with resistance from the owners of the kraals and that they would be required to pay for the dung.

In October 1992 it was found that the digester had not been fed for more than two months, mainly because of the lack of water due to the drought, while the regular straying of the cattle at the time probably also played a part. Feeding started again in January 1993 after the situation had improved, but virtually no gas was produced at the time, as the digester mainly contained spent slurry. The WRF subsequently assisted the family with the emptying and restarting of the digester in March 1993.

9.4.4 Water usage

The family mainly used water for domestic purposes such as cooking, drinking, dish washing, bathing and doing the laundry. One of the teenage boys in the family, Herbert, seemed to be responsible for the collection of water, although he was assisted by other family members at times. In general water was collected once or twice a day, depending on the distance to the source, by using 25 ℓ containers stacked onto a wheelbarrow.

In 1990 the family reportedly used 100 ℓ of water per day, which they usually collected from a communal tap less than 50 m from the homestead (Trace 1990). During the project period another tap was installed even closer to the Mathabela homestead, which enabled them to fetch water when required. However, it appeared that water was frequently not available from these sources. For example, in December 1991 family members mentioned the need to fetch water for cooking and drinking purposes (75 ℓ/day) from other sources, including a communal tap approximately 2 km from the homestead, a handpump approximately 1 km away and a tap on a private property less than 1 km from them. Water for other purposes, such as bathing and the feeding of the biogas plant, was sometimes obtained from a river bed. The fetching of water over long distances for the feeding of the digester was the responsibility of the boy who was feeding the plant at the time. Shortly after the installation of the plant, the possibility of storing water to feed the biogas plant when water could not be collected, was suggested by Freddy Mathabela. This was encouraged by members of the project team, but it was never implemented by the family.

In October 1992 family members indicated that they were using 75 ℓ of water per day, which was fetched mostly from a communal tap approximately 1.2 km from the homestead, although on some days water could be obtained from a tap less than 500 m away from them.

The impact of the drought was evident from the fact that this water had to be used for the watering of the cattle in addition to the normal domestic purposes.

9.4.5 Energy use

The energy use of the family changed significantly during the project. A distinction will therefore be made here between three different periods, based on the fuels used by the family at the time: The period prior to the installation of the biogas plant, the period immediately following the installation of the plant, and the final year of the study.

Prior to the installation of the plant, firewood had been the only fuel used by the family for cooking and heating purposes (Trace 1990). Every 2-3 days a wheelbarrow load of wood was either collected or bought at a cost of R 2. If a wheelbarrow load is assumed to contain 34 kg of wood (Griffin *et al* 1992: 10), this would indicate that the family used ± 400 kg of wood per month. This would have cost R 24/month if all of it had been purchased. According to Trace (1990) the family cooked once a day on a woodfire for approximately 90 minutes. This was usually done outside, where the fire was shielded from the wind by a brick structure. They heated approximately 10 ℓ of water twice a day for bathing, also using the woodfire for this purpose. The family apparently used no paraffin at the time, and was dependent on candles for lighting purposes.

After the installation of the biogas plant, biogas was used for cooking purposes by both Mrs Mathabela and Marie Antoinette, who was Freddy's fiance at the time and visited the family once or twice a week. While Marie Antoinette clearly preferred the use of biogas to wood whenever possible, Mrs Mathabela seemed reluctant to discard the woodfire, at least partly for personal reasons related to culture and tradition. The family cooked a large meal of pap and meat/gravy every day, of which the latter was cooked on biogas, while a woodfire was used to cook the pap in a large three-legged pot. According to Freddy Mathabela this was done mainly because of the length of time required to cook the pap on a biogas burner. However, biogas was sometimes used to cook small quantities of pap. As pap formed the bulk of the food consumed by the family, biogas had clearly not been adopted as the main cooking fuel.

It was difficult to establish how often the biogas was used for other purposes. In July 1991 family members indicated that the gas was used twice a day for water heating and twice a week for ironing, which involved the heating of a metal iron on a biogas burner. During interviews conducted in December 1991, it was established that most family members used biogas almost every day to heat water for bathing (approximately 2 ℓ/person/day) and that most of them did ironing about once a week. Mrs Mathabela also used the gas to heat water for tea on a regular basis. Family members clearly valued the gas for its convenience when performing these tasks, and indicated that the heating of water enjoyed priority when the quantity of gas was insufficient. Biogas therefore played an important role as a supplementary fuel in the household.

It is doubtful that the use of biogas significantly reduced the family's fuelwood usage, although family members claimed that this was the case. In July 1991 the family reported that they had purchased a bakkie load of wood which would last them throughout the winter, at a cost of R 75. Using the conversion factor reported by Griffin *et al* (1992: 10), this was estimated to be approximately 650 kg of wood. If this had been the only wood used by the family during the winter, it would have constituted a reduction in the fuelwood use of the family as compared to that reported by Trace (1990).

In October 1992 family members indicated that the woodfire was generally made outside in summer. It was observed at the time that the fire was made in a small enclosure formed by means of cement bricks. In the winter, on the other hand, the fire was usually made inside where it could provide for space heating as well as for cooking. According to Marie Antoinette it often happened that Mrs Mathabela would make a fire on the floor of the kitchen rondavel during winter, even when Marie Antoinette was preparing food on a metal woodstove in another room.

During 1992 a liquid petroleum gas (LPG) burner was acquired by Freddy Mathabela at the same time that he married Marie Antoinette. In October 1992 it was found that the family were using a mixture of fuels, including wood, LPG and biogas for cooking and heating purposes and candles and paraffin for lighting. However, the paraffin was used only by Marie Antoinette and Freddy, while the rest of the family still used candles for lighting purposes. All the wood was bought from a merchant close to the homestead. Generally the fuels were used for the same purposes as discussed above, but an additional use mentioned was the heating of water to wash dishes. The daily meal, comprising a large pot of pap and meat/gravy, was prepared by Mrs Mathabela on weekdays when Marie Antoinette was attending school, while the latter cooked over weekends. Apparently this food also served as supper for Mr Mathabela and Freddy who were at work during the day, but it was not reheated for this purpose. Small quantities of pap were sometimes cooked for breakfast.

Biogas production was very low in October 1992, mainly because the digester had not been fed for more than two months at the time, and because problems were experienced with the gas burners (see Section 9.4.7). The biogas that was available appeared to be used mainly by the teenage boys for ironing. Marie Antoinette used the LPG burner for all cooking purposes other than the preparation of the large pot of pap. She indicated that the LPG burner provided for faster cooking than biogas. Mrs Mathabela refrained from using the LPG as she was afraid to do so. Although Marie Antoinette and Freddy were the only family members who used the LPG burner, the others also benefitted from this as it was sometimes used to boil water or to do ironing for other members of the family, and was used regularly to cook meat/gravy for the whole family.

In October 1992 an attempt was made to obtain estimates of the quantities and costs of the fuels used by the family on a monthly basis. In Table 9.2 the estimated monthly consumption of fuels, and expenditure on fuels by the Mathabela family are given, which have been calculated using the information obtained from family members. As shown in the table, the estimates that were given by different family members were highly disparate in some cases, e.g. for fuelwood. The estimated fuel use and expenditure of the Mathabela family is compared with the mean household fuel consumption by users of the fuels in the village of Okkerneutboom, which is relatively close to Timbavati (Griffin *et al* 1992). The calculated expenditure given in the last column was determined by multiplying the quantities of fuels reported by the family with the prices paid for those fuels in Okkerneutboom at the time, which were reported by Griffin *et al* (1992).

Table 9.2: Reported monthly energy use and expenditure of the Mathabela family in October 1992. The mean values for households in Okkerneutboom who use the fuels are given for comparative purposes.

Fuel	Monthly use (Mathabela family)	Mean monthly use (users of fuels in Okkerneutboom)	Monthly expenditure reported by Mathabela family (rand)	Calculated monthly expenditure (rand)
Woodfuel	140-220 kg	251 kg	26-77	18.70-28.10
Candles	42-60	28	11-22	16.80-24.00
LPG	10 kg	10.4 kg	14	27.70
Paraffin	10 ℓ	17.3 ℓ	10	13.80
Total			52-123	77-94

Source: Information on energy use in Okkerneutboom obtained from Griffin *et al* (1992).

9.4.6 Use of the digested slurry

The Mathabela family grew mealies and vegetables like spinach, cabbage and tomatoes at the homestead for their own use, particularly during the summer months. During 1991 a small patch of vegetables was planted within the fence surrounding the biogas plant and digested slurry was used as fertiliser. Mrs and Mr Mathabela were both very positive about the use of the slurry and felt that it benefitted the growth of the vegetables. However, the slurry was only applied to the soil during the growing season. No vegetables were grown during the dry winter season, or during the severe drought which affected the area particularly in 1992. At times the digested slurry was used as fertiliser by some of the neighbours of the Mathabela family. For example, a man was once observed collecting slurry in a bucket strapped to the back of his bicycle.

9.4.7 Maintenance of the biogas plant

A distinction can be made between one-off repair tasks, regular maintenance tasks of a simple nature, and major maintenance tasks. As discussed in Section 8.2.3, the PVC inlet and outlet pipes of the biogas plant were partly exposed because of the height of the biogas digester above ground level. At the time of the construction of the plant, the Mathabela family agreed to cover these with plaster to protect them against UV-radiation. Mr Mathabela subsequently covered the exposed inlet pipe with plaster, and in October 1992 he indicated that he was planning to cover the exposed outlet pipe as well. He also destroyed an emerging termite nest which had threatened to undermine the mixing box.

Basic maintenance tasks which had to be performed, mainly to ensure the proper functioning of the gas burners, included the repair and cleaning of the burners and the clearing of condensate from the gas pipeline. The burners are each fitted with a brass control valve. The handle of the valve is secured by a nut which has to be tightened periodically. In addition, the flame ports of the gas burners have to be cleaned regularly to remove a hard deposit which form when the burners are used. Although a water trap was fitted in the pipeline, water still condensed inside the pipes between the water trap and the gas burners. Water removal would probably have been more effective if the pipeline had been laid underground, as it would have allowed the gas to cool sufficiently before reaching the kitchen.

Some of these tasks were performed a number of times by members of the family under supervision of the WRF. The family appeared to have no difficulty with the draining of water from the gas pipe. However, during the visit by the author in October 1992, the burners were found to be in a poor condition. One of them could not be used at all, while the other provided only a very weak flame. Family members complained that the burners were not operating as well as before, but they had not reported it to the WRF. One of the reasons for the state of the burners was that the nuts attached to the control valves had loosened to the extent that gas flow could no longer be controlled properly and gas had started to leak from the valves. Mr Mathabela had attempted to seal the leak by wrapping a plastic bag around one of the valves. In addition, the flame ports of the gas burners had become blocked, partly as a result of the deposit which formed when they were used. IN addition, soot had collected on the burners, which were kept in the kitchen rondavel where a fire was made quite often.

In February 1993 the family was visited by a CSIR technician, who supervised the replacement of the control valves on the burners and the cleaning of the flame ports. The two teenage boys in the household were also instructed on the continued maintenance of the burners and on the dangers involved when gas leaked inside the kitchen rondavel. The family were provided with two metal boxes which fit around the burners and can be used both to cover the burners when they are not in use, and to act as heat shields, as shown in Figure C.8 in Appendix C.

The major maintenance tasks required, were the repainting of the gas drum on the outside every second year, while the gas pipeline would have needed replacement when it developed leaks. When the gas drum was removed to install the gas deflecting ledge one year after the construction of the plant, it was observed that the paint on the inside of the drum had started to peel off. This probably resulted because of the inadequate removal of oxide from the steel surface prior to painting. It was therefore decided to clean and repaint the drum on the inside and outside to ensure that it was in a good condition before the responsibility for its maintenance was handed over to the family. During March 1993 the gas drum was removed from the digester and cleaned and painted by the family with the assistance of the WRF.

It was also decided to replace the gas pipeline before the end of the project, as it had been in use for $\pm$ 30 months at the time. The installation of a metal pipeline was considered, mainly because its lifetime would be much longer than that of the reinforced hosepipe which served as gas pipeline. However, this was not done as the family were planning to relocate their kitchen in the near future. The gas pipeline was subsequently replaced during February 1993 by the teenage boys in the household under supervision of a CSIR technician. The boys were also instructed on the manner in which the pipeline could be checked for leaks.

9.4.8 Responsibility for the biogas plant

The family had not been asked to contribute financially to the biogas plant when it was installed, because it had been the first biogas plant that was constructed by the project team, and it had been the expected that the design would need some improvement. This clearly influenced the response of the family to the technology, as it provided them with a free source of energy in monetary terms. It also seemed to have resulted in some confusion about the ownership of and therefore the responsibility for the plant, and during the first year of operation the family seemed to look to the CSIR and the WRF to provide them with relatively small items required for the operation of the plant. During the first 18 months of operation, the WRF had kept regular contact with the family as some monitoring of the system was conducted. Although attempts were made during this period to instruct family members on the maintenance of the gas burners and gas pipeline, the family seemed to remain dependent to some extent on the WRF for these maintenance tasks.

In the latter part of 1992 the family were left more to their own devices and in this period the feeding of the plant ceased and the gas burners broke down almost completely. While the feeding of the plant was virtually impossible at the time because of the difficulty to obtain water, the fact that the family did not approach the WRF about the state of the gas burners was of concern. This could have been partly as a result of the low gas production at the time, which did not allow extensive use of the gas. However, the main reason appears to have been the confusion of responsibility within the family. Most family members seemed to have expected of the WRF to detect the problem, or that Freddy Mathabela would report the problem to the WRF. In October 1992 it was established that Mr Mathabela was taking most responsibility for the biogas plant, although he emphasised that he expected of Freddy to take the responsibility, as the latter had worked actively towards the installation of the plant at their home. However, Freddy was clearly not fulfilling this role.

A family meeting was therefore arranged in February 1993 by a CSIR community worker, where the utilisation of the biogas plant by the family was discussed. It was explained to the family that they would have to take full responsibility for the plant in the future, although they would be able to approach the WRF for advice and assistance. They were given the option to contribute financially to some essential maintenance tasks if they wished to continue using the gas. The family decided in favour of the continued utilisation of the plant and an arrangement was made regarding the payment for the gas burner valves and a small contribution towards the painting of the gas drum. The family undertook to assist with the replacement of the gas pipeline and gas burner valves, as well as with the cleaning and painting of the gas drum (see Section 9.4.7). The two teenage boys in the household were given the responsibility of maintaining the gas pipeline and burners, while Freddy was given the responsibility of approaching the WRF if assistance was required by the family.

9.4.9 Conclusions

During the first twelve to eighteen months of the project the Mathabela family had often expressed their appreciation regarding the convenience of biogas as a fuel. However, this situation changed significantly during 1992, when Marie Antoinette, who seemed to have been the main user of biogas up to that stage, acquired the use of an LPG burner. During the same period problems developed with the biogas burners, which further discouraged the use of biogas. Marie Antoinette's observation in October 1992 that LPG cooked much faster than biogas may have been influenced largely by the problems with the biogas burners. Although the family were discouraged somewhat by these problems, they valued the biogas sufficiently to pay something towards the repair of the system. At the time most of the family members did not have access to the LPG burner, but were dependent on firewood for purposes such as ironing and water heating which had previously been met by biogas.

The problems that were encountered by the family related mainly to shortages of manure and water, as well as the maintenance of the biogas plant. The availability of dung proved to be a constraint in spite of the relatively large number of cattle owned by the family. As discussed in Section 6.2.3, this could be attributed mainly to the unfavourable grazing conditions on communal lands, which may have important implications for the minimum number of cattle required to operate a biogas plant in the former homelands. Water availability proved to be an important constraint, even in this area where water is generally available from communal stand-pipes. This became a severe problem during the drought when water had to be collected from distant sources. The effective utilisation of the technology is clearly only possible if water is conveniently available and in areas which are not particularly prone to drought.

While some maintenance of the system had been undertaken by family members, it is uncertain to what extent they have the ability or the aptitude to keep the system in a running condition without any outside assistance. They required support with relatively minor tasks and were dependent on the WRF for arranging major operations such as the repainting of the gas drum. Families with an established ability to do repair work would be in a better position to handle the maintenance requirements of a biogas digester. Generally this experience has highlighted the need for the support of users of the technology in the former homelands. The biogas system was also not managed as effectively as it could have been. For example, provision could have been made for storing the fresh dung on days when no water was available for mixing the slurry, so that it could be added to the plant at a later stage. The digested slurry was also not fully utilised as fertiliser. Furthermore, responsibility for the feeding and maintenance of the digester was generally not clearly allocated. This experience has indicated that, while the availability of sufficient quantities of manure and water is a precondition for the successful implementation of biogas technology, the skills and the resources of the users are also of great importance.

9.5 Responses of more affluent households

As discussed in Section 6.2.3, the experience with the biogas unit at the Mathabela family had indicated that a relatively large number of cattle would be required by smallholders in the former homelands, under present grazing conditions and with current kraaling practices, to provide sufficient quantities of manure for the operation of a biogas plant. During the biogas studies discussed in Section 9.3, no specific attempt had been made to extract the response of smallholders who had sufficient manure for this purpose. It was therefore decided to conduct in-depth interviews with a few households who would be able to utilise the technology, in the area where the biogas plant had been installed.

In October 1992 the author interviewed three households in Welverdiend, one of the villages which had been included in the study by Griffin *et al* (1992). This village was selected because of the relatively high number of cattle owned by households (6.5 per household on average) compared to the other villages, although it also had the lowest annual rainfall (560 mm) of the villages that were surveyed. The three households were specifically selected because they owned relatively large numbers of cattle. However, all of them had lost about half of their cattle during the severe drought in the area, as was the case with most of the families in the area who owned cattle. As the visit took place during one of the worst periods of the drought, and people in the area were clearly traumatised by the great number of cattle losses, a community leader was consulted prior to the interviews to establish whether it would be in order to discuss biogas technology under the circumstances. He ensured us that it would be in order to do so. Moreover, the families themselves indicated that they were willing to participate in the interviews.

Aspects covered during the interviews included household energy and water usage, farming practices and the response of households to biogas technology. Care was taken not to "sell" the technology, but to present it as realistically as possible, emphasising aspects such as the need for maintenance, the integration of the plant into the farming system and the cost of a plant. The households were specifically asked about their attitudes to obtaining a loan, as this could be a way by which households with insufficient cash resources could fund the installation of a biogas plant. As it had not been possible to arrange a visit to the biogas plant at the Mathabela homestead by the respondents, a poster of the plant was used during the interviews as illustration. However, two of the respondents expressed the need to observe the technology in operation before an opinion could be formed on the matter. In two of the households women were interviewed, as the husbands were not present. The Mogope family was relatively affluent and their circumstances can be summarised as follows:

- The family comprised two adults and four children.
- Their income was in excess of R 1500 per month.
- They owned 24 head of cattle at the time (previously 42).
- They used a gas fridge, and used paraffin for lighting and some cooking.
- They owned a hi-fi which was operated from a car battery.
- They employed young boys to collect wood for cooking purposes.
- The expenditure on energy was in excess of R 100/month.
- They used 100-200 ℓ of water per day, which had to be collected from a communal tap.

Mrs Mogope was dissatisfied with LPG, mainly because she found it expensive. She was emphatic about her preference for electricity. The cooking for the household was generally done by a family member, while Mrs Mogope used a paraffin burner when she needed to do some cooking. She was not particularly interested in biogas, although she said that she might consider using it once she had seen a plant in operation. However, she was concerned about the options available to an owner if the plant would break down. Although the family had never borrowed money from a bank, Mrs Mogope said that they would consider using such a facility if they had sufficient information on the matter.

The response of Mrs Mogope highlighted the fact that wealthier households in the former homelands might have expectations which does not allow for the use of biogas, as well as having the means to fulfil these expectations to some degree. While cost considerations seemed to determine the fuel use of the Mogope family to some extent, and apparently prohibited the use of a gas stove owned by the family, this did not prevent decisions in favour of convenience. The latter was clearly of great importance to Mrs Mogope, who preferred not to cook on an open fire.

The circumstances of the second household interviewed, the Nyalungu family, can be summarised as follows:

- The family comprised four adults and four children.
- Their total monthly expenditure was R 1700, including Mrs Nyalungu's income of R 700, and R 1 000 from her husband's savings (he had recently become unemployed).
- They owned 20 head of cattle (previously more).
- They collected wood twice a month by hand, taking six hours each time.
- They used paraffin for lighting and fast cooking, and used candles for lighting.
- They used a small quantity of coal (80 kg/year).
- They used PM10 batteries in a radio.
- Their energy expenditure was approximately R 53/month.
- They used 75 ℓ of water per day, which was collected from a communal tap.

Mrs Nyalungu expressed a need for a more convenient energy source that would be more simple to use and that would save time. She was positive about the ability of both gas and electricity to fulfil these requirements. However, cost considerations prevented her from making decisions in favour of convenient energy sources. This was the case in spite of the relatively high level of household expenditure that was reported. This could indicate that energy convenience was not of a high priority in the household as a whole. Unfortunately Mrs Nyalungu did not want to express an opinion on biogas as the technology was strange to her, and her husband was not present at the time. However, she was concerned about the costs and risks involved when adopting the technology.

The third household interviewed, the Ngobeni family, only had eight cattle at the time, as they had lost a similar number during the drought. Mr Ngobeni was a pensioner, and the household had a monthly income of R 580. The senior wife in the household did not participate in the interview, although she was at home at the time. According to Mr Ngobeni, they were comfortable with the use of firewood as they had used it for many years and were unable to afford alternative fuels. He was concerned about the safety aspects of gas usage. Although he expressed an interest in biogas, this may have been an attempt to be polite.

Although of limited value, these interviews have provided some indication of the responses that might be forthcoming from potential users of biogas technology. In contrast with the Ngobeni family, the use of gas was acceptable to both Mrs Mogope and Mrs Nyalungu, with no concerns being expressed about its safety. This may have been expected in the light of the fact that more affluent households in the rural areas often use LPG for domestic purposes. Unfortunately none of the respondents were willing or able to provide an estimate of what they would be prepared to pay per month for the energy source of their choice.

9.6 Target group among smallholders

As discussed in Section 9.4.9, the experience with the Mathabela family plant has indicated that the successful implementation of biogas technology is dependent on a number of factors, which include technical considerations such as the availability of sufficient quantities of manure and water, as well as the skills and the resources of the users of the technology. In this section an attempt will be made to characterise the smallholders in the former homelands, as well as newly established black small farmers in South Africa (see Section 2.2), who would be able to implement the technology successfully. It is informative in this regard to consider the requirements which have to be met by small farmers in Tanzania before they will be considered for the implementation of biogas units (Kellner and Lwakabamba 1985: 316) (Sasse *et al* 1991: 13). They are required to:

- have sufficient income to buy a plant or repay a loan
- be educated enough to understand a biogas system
- have a level of technical awareness that would enable them to operate and maintain a plant

These requirements reflect the fact that small farmers need access to resources, e.g. financial resources as well as knowledge and skills, in order to utilise the technology effectively. According to Bembridge (1990: 19) smallholders in the former homelands have generally had considerably less access to resources, such as extension services, credit, education and training etc, than commercial white farmers. This has hampered agricultural development in these areas, and would almost certainly limit the implementation of biogas technology. However, a future agricultural development policy is expected to place particular emphasis on the provision of training opportunities and support services to black small farmers in the former homelands and in other areas.

The capital costs involved in installing a biogas plant is an important factor determining who is able to adopt the technology. Biogas technology therefore tends to be adopted by the wealthier households in rural areas, who may have sufficient cash available to install a biogas plant, or could possibly obtain loans from banks. Even where subsidies are offered for this purpose, the technology may not be adopted by poorer farmers. For example, in Tanzania difficulties have been experienced with the dissemination of the technology among small farmers, even when subsidies were offered, mainly because of the small cash incomes of these households (Kellner 1991a: 8). The main group in Tanzania who have adopted the technology is described as "well-to-do" farmers who tend to be innovative and business-oriented (Kellner and Lwakabamba 1985: 318), with additional incomes from non-farming activities (Kellner 1991a: 8). This is similar to the situation in India, where 75 % of plant owners belong to a high socio-economic group in the rural areas, the rest belonging to a "middle class" (Kijne 1984: 59). These groups generally comprise the richer land-owners in the rural areas, who have relatively high levels of education and social status, although there are exceptions.

As discussed in Section 2.2, there is a small group of smallholders in the former homelands (13 % of the rural population) who have been relatively successful as farmers (Bembridge 1990: 21). In his study of agricultural development problems in the Transkei, Bembridge (1984: 532) established a profile of the more successful small farmers in the area. For this purpose he considered the more productive farmers in terms of total crop production and livestock sales, and also analyzed the "best farmers" in different areas, who were identified by extension workers (Bembridge 1984: 533). He found that the more productive farmers tended to:

- be employed outside the rural areas
- be able to invest more in their farming
- be more motivated to achieve an acceptable level of income
- fall in the younger age groups
- have a relatively high level of education and knowledge of farming
- adopt modern technology
- have a higher level of managerial aptitude
- have more progressive attitudes towards farming
- have larger farm holdings and more implements
- enjoy a higher standard of living and socio-economic status
- participate in local organisations
- have greater contact with information sources

The level of managerial aptitude appeared to be a very important characteristic of productive farmers, while education and training also had a significant influence on farming progressiveness (*ibid*). Female farmers were found to be significantly less productive than males, which was attributed partly to the burdens placed on women in the form of household chores and child care, and their lack of training (*ibid*). The "best farmers" in different areas showed similar characteristics to those listed above. In addition it was found that they generally:

- managed their own farms
- more often had vocational training
- adopted more modern farming practices
- felt that they were making a good living out of farming
- were more motivated to improve the social amenities and quality of life in the area

These farmers derived the greater part of their income from farming (63 % compared to 10 % for the average farmer), and earned ten times more income from farming than average farmers (*ibid*). It therefore would appear that this group of farmers in the former homelands would be most likely to implement biogas technology successfully.

In conclusion it is necessary to comment on the implementation of community biogas plants, i.e. plants which are owned and utilised by a group of families or farmers, which are often seen as the manner in which the technology could be made accessible to poorer households. Experience has shown that such plants are very difficult to implement successfully. In India, for example, difficulties were encountered because of class, caste and faction differences within communities, as well as a lack of organisational and managerial skills (Kijne 1984: 60). Kyu and Muturi (1986: 149) have argued that *household* biogas plants would be more appropriate to African farmers than multiple-family or village plants because of the rather scattered nature of rural villages and the relatively low level of organisation of rural African societies compared to Asian societies. In Botswana the implementation of biogas plants owned by syndicates of cattle owners had met with difficulties, mainly as a result of a lack of cooperation between members (Woto 1988: 16). For these reasons no attention had been given in this study to biogas plants which are owned communally.

9.7 Conclusions

The experience with the Mathabela family biogas plant has indicated that, while the availability of sufficient quantities of manure and water is a precondition for the successful implementation of biogas technology, the skills and resources of the users are also of great importance. The family encountered various problems which were mainly related to shortages of manure and water, and the maintenance and management of the biogas plant.

In other countries where biogas technology has been implemented, it has been mainly the more affluent and skilled farmers who have adopted the technology. In South Africa a small percentage of smallholders in the former homelands appear to have the skills, and to some extent the resources, which are required to implement biogas technology successfully. This group is expected to grow in the future if a land reform programme is implemented and greater emphasis is placed on small-scale agricultural development. However, the inadequate nature of the existing support services for smallholders in the former homelands is likely to hamper the implementation of the technology in these areas.

CHAPTER 10
CONCLUSIONS

10.1 Potential users of biogas technology in South Africa

Three groups of potential users of biogas technology in South Africa have been considered in this study, including smallholders and farmers who may utilise the technology for energy production on a small scale, institutions such as schools in rural areas which may utilise the technology as a sanitation option and for energy production, and large-scale intensive farming enterprises which may acquire the technology for purposes of waste stabilisation as well as energy production on a relatively large scale.

The study has focused mainly on the possible utilisation of the technology by smallholders in the former homelands, which comprise 69 % of the rural population in these areas. This group includes approximately 238 000 "progressive" smallholders, who derive some income from the sale of produce and/or livestock, but usually do not produce adequate food for their own use, as well as approximately 1 028 000 smallholders who generally do not sell any crops or livestock. In addition, small farmers who may be established as part of future land reform and agricultural development programmes, have also been considered.

10.2 Operational aspects of biogas technology

The concentration of the slurry in simple biogas plants which are operated on a continuous basis, should generally be between 6 % and 13 % total solids, depending on the type of substrate used. Substrates with a low carbon to nitrogen ratio, such as poultry excreta, need to be diluted more to prevent ammonia toxicity in the digester, while cattle manure can be digested successfully at a total solids concentration of 13 %.

Simple biogas plants are generally operated at ambient temperatures. As digestion becomes unsatisfactory below 20 °C, an area is generally only suitable for the implementation of simple biogas technology if the mean ambient temperature does not remain below 15 °C for a substantial length of time. Large-scale biogas plants can also be operated satisfactorily at relatively low temperatures. Similar gas yields can be achieved in digesters which are operated at different temperatures, if the retention time of the digester at the lower temperature is suitably increased. Small-scale biogas plants are generally operated at retention times of 60-80 days and even longer, for reasons such as the small quantities of substrate available.

The optimum pH for digesters is generally within the range of 6.8-7.2. The accumulation of acid in the slurry could occur as a result of sudden changes in the operating conditions or the presence of toxins in the slurry. However, toxicity is not a common problem in digesters which utilise natural substrates such as agricultural wastes. Substrates with a C/N ratio less than eight, e.g. human excreta and poultry excreta, may lead to excessive levels of ammonia in the slurry, which is toxic to the bacteria.

10.3 Design and construction of biogas plants

The advantages of the floating-drum plant are such that this design would be an attractive option in many instances. Its main drawback has been the costs associated with the maintenance and replacement of the mild steel gas drum. However, a high-density polyethylene (HDPE) gas drum may provide a suitable alternative, as it appears to satisfy most of the requirements for a gas drum such as low maintenance and a relatively long lifespan.

Based on cost considerations it would appear that the most suitable floating-drum design for digester sizes of 10 m^3 and less, would be the ferrocement digester with the HDPE gas drum. Larger plants would have to be provided with a tapered brick digester, because of the restrictions on the size of the ferrocement digester. This digester could also be built where a high water-table or a shallow rock layer prevents the excavation of a deep hole, or if the mould required for the construction of the ferrocement digester is unavailable.

The fixed-dome plant also has a number of important advantages. In other countries the main advantage of this design has been its low cost when constructed of bricks. However, the high level of skills required for the successful construction of a brick dome would severely limit its implementation in South Africa, as these skills are not generally available in the country. The ferrocement fixed-dome design seems to be a viable alternative to the brick design, as the risk of plant failure is reduced considerably, while most of the skills required are available in rural areas. The costs of this plant in rural areas were found to be considerably lower than either of the floating-drum plants built during this study.

The flexible cover plant developed during this study was relatively simple to construct, while the costs of this plant were found to be significantly lower than the other plants considered. A suitable material for the gas holder has also been identified. This plant therefore seems to have considerable potential for large-scale applications, but additional research would be required to develop a large-scale plant which could be implemented in South Africa.

10.4 Use of biogas as energy source

Locally available gas burners have been adapted successfully for use with biogas, although these burners appear to be less efficient than specially made biogas burners. The biogas requirements of rural families for cooking and related purposes have been estimated as 2-2.5 m^3 per day, which are similar to reported figures for other countries. The estimated useful costs of biogas in rural areas, which is produced in small-scale biogas plants, appear to compare favourably with the costs of paraffin and liquid petroleum gas in rural areas, particularly for gas which is produced in the ferrocement fixed-dome plant.

10.5 Implementation of biogas technology on farms and smallholdings

Not all the manure which are produced on farms and smallholdings would be available for use in a biogas plant, while the properties of the available material may differ considerably from the properties of fresh manure. The quantities and the properties of the waste that is available would depend on farming practices such as the housing of animals and the cleaning of stables.

Indications are that a minimum number of seventeen cattle might be required by smallholders in the former homelands in order to utilise biogas technology. This is considerably more than the required minimum number of cattle in other countries for similar conditions, i.e. the confinement of the cattle for part of the day only. This could be attributed in part to the deteriorated state of the grazing lands in parts of the former homelands, which would result in relatively low manure yields. However, it would be necessary to assess the situation in particular areas, as the grazing conditions could differ substantially.

The most viable applications of biogas technology on small farms are found where mixed farming is practised, so that the availability of manure for the feeding of the digester is combined with a need for the digested slurry as fertiliser. In the former homelands the most feasible use for digested slurry would appear to be as fertiliser in home gardens, which can be fairly large. Parts of the Transkei, KwaZulu and Bophuthatswana appear to have the greatest potential for the implementation of biogas technology in the former homelands, based on cattle figures in these areas.

10.6 Utilising human excreta for biogas production

A biogas plant which utilises human excreta should primarily be seen as a sanitation system with the additional benefit of gas production. The properties of undiluted human excreta, such as its low C/N ratio, may present some difficulties when it is utilised as a substrate in biogas plants. On the other hand, the wastewater from ablution blocks would generally be too dilute to provide satisfactory gas production, and measures would therefore be required to reduce the quantities of water entering a digester. Relatively low volumetric gas production rates are generally achieved in biogas plants utilising human excreta.

The possible health risks posed by pathogenic organisms associated with human excreta need to be considered in the design and operation of biogas systems. The most suitable plant designs for the utilisation of human excreta are the fixed-dome plant, the floating-drum plant with a water-jacket, and a digester with a separate gas holder, as all of these provide for the enclosure of the digesting material.

In most rural areas it would be necessary to implement biogas systems which would require the disposal of the effluent at the institution involved, as desludging services would generally not be available. The destruction rates of pathogens in the digester would therefore be of particular concern. Higher destruction rates are generally achieved at high temperatures or long retention times. In simple biogas plants which are operated at ambient temperatures, retention times of 80-100 days would generally be required to ensure satisfactory destruction rates. The disposal and possible utilisation of the effluent would require proper management to ensure that risks are minimised. As most schools in rural areas would probably not have the resources required for this purpose, the application of biogas technology at these schools does not seem very promising under current conditions.

10.7 Utilisation of biogas technology by smallholders

The experience of the Mathabela family has indicated that the successful implementation of biogas technology is dependent on a number of factors, which include considerations such as the availability of sufficient quantities of manure and water, as well as the skills and resources required by the users of the technology to maintain the plant in the long term and manage the plant effectively.

In other countries where biogas technology has been implemented, it has mainly been the more affluent and skilled farmers who have adopted the technology. In South Africa a small percentage of smallholders in the former homelands appear to have the skills, and to some extent the resources, which are required to implement biogas technology successfully. This group is expected to grow in the future if a land reform programme is implemented and greater emphasis is placed on small-scale agricultural development. However, the inadequate nature of the existing support services for smallholders in the former homelands is likely to hamper the implementation of the technology in these areas.

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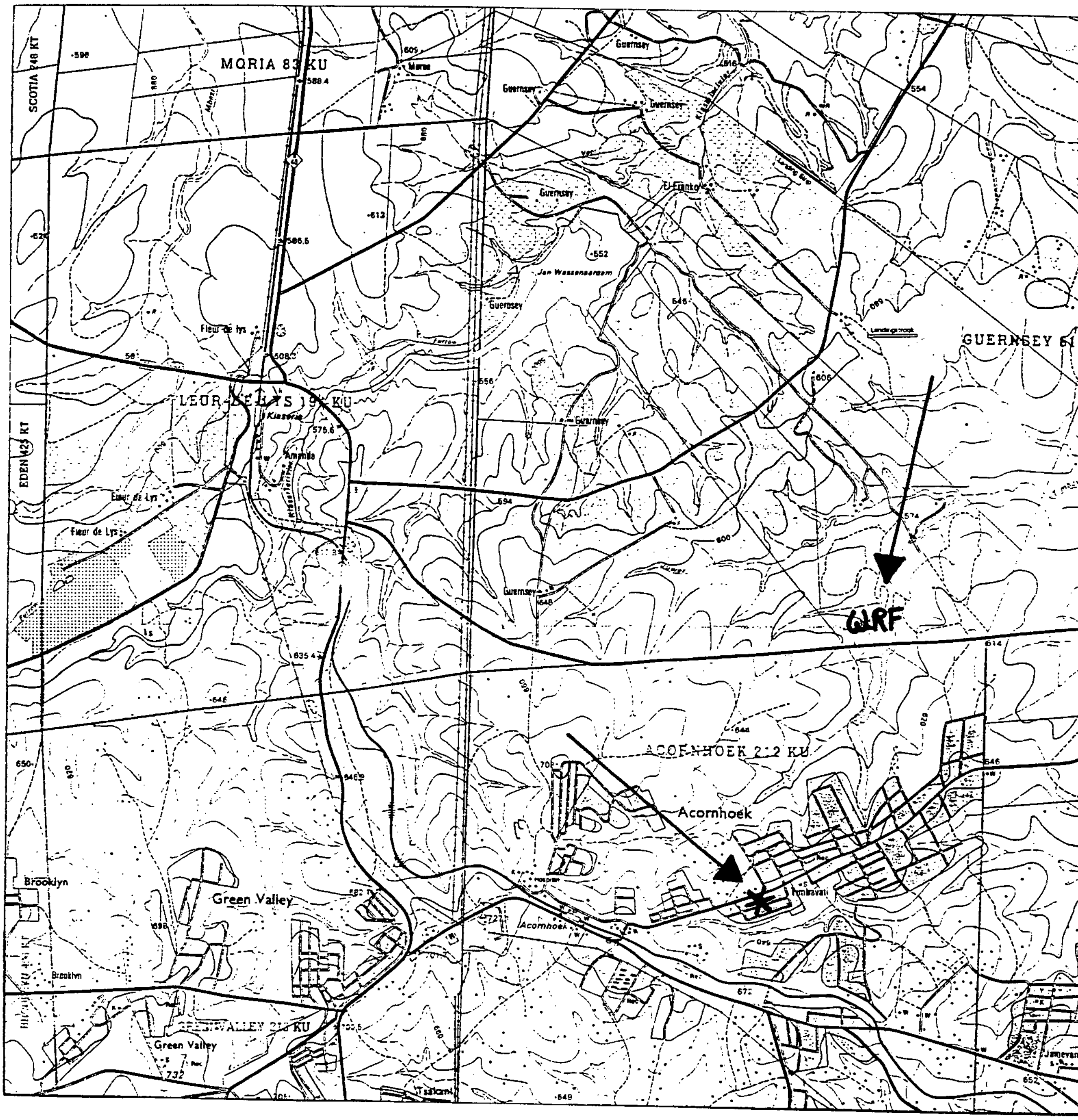
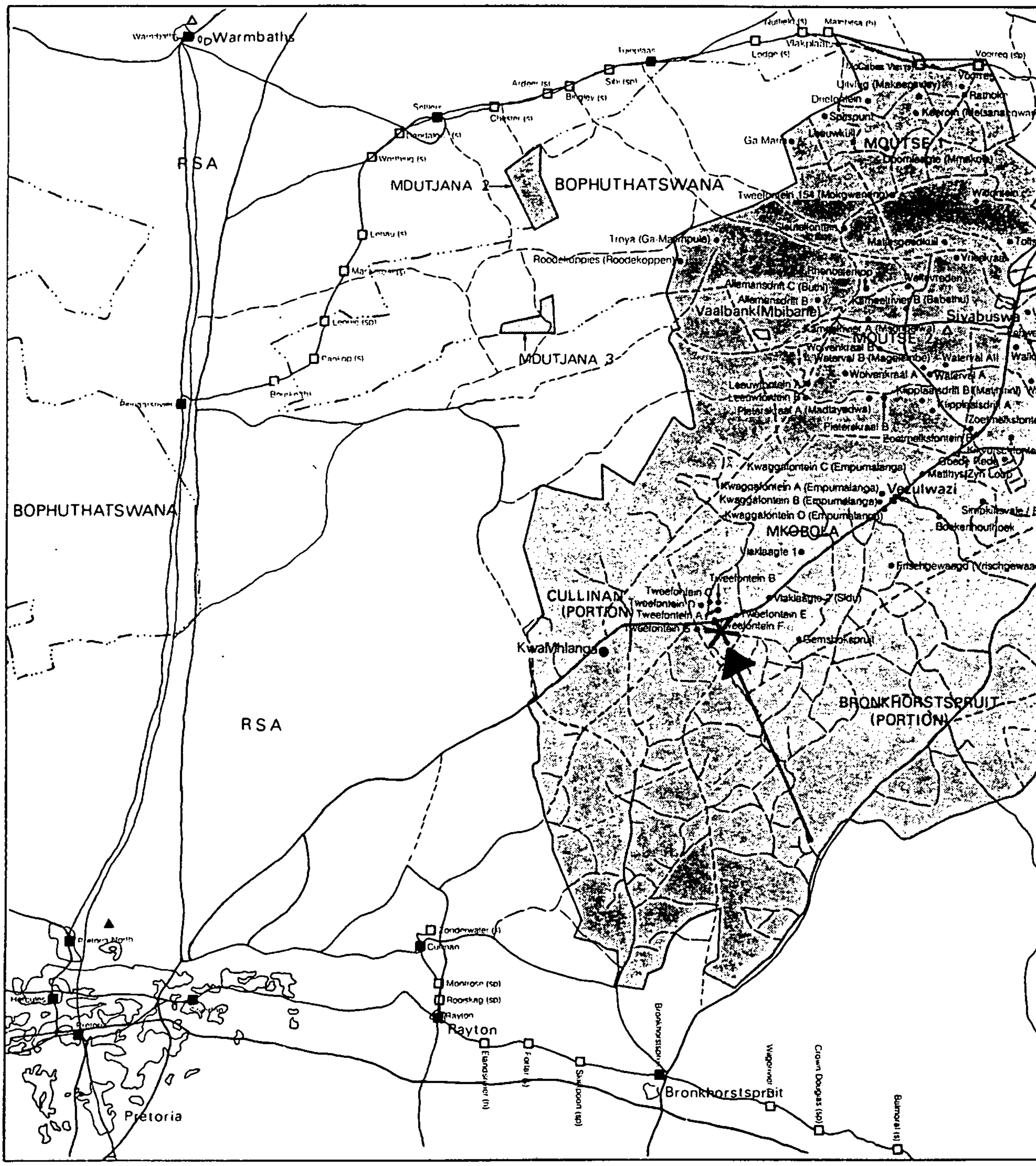
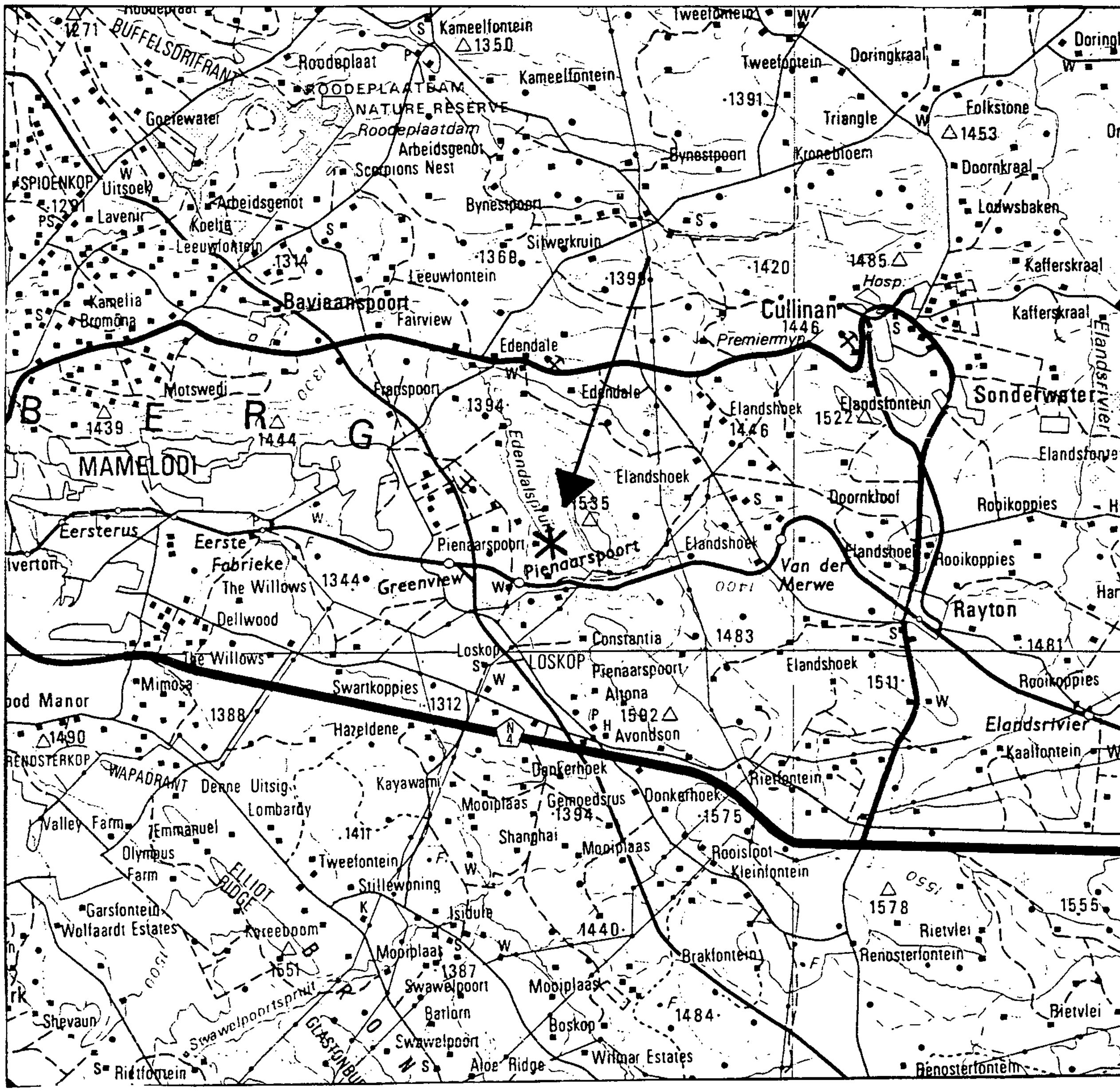
Appendix A: Maps indicating the locations of the pilot plants



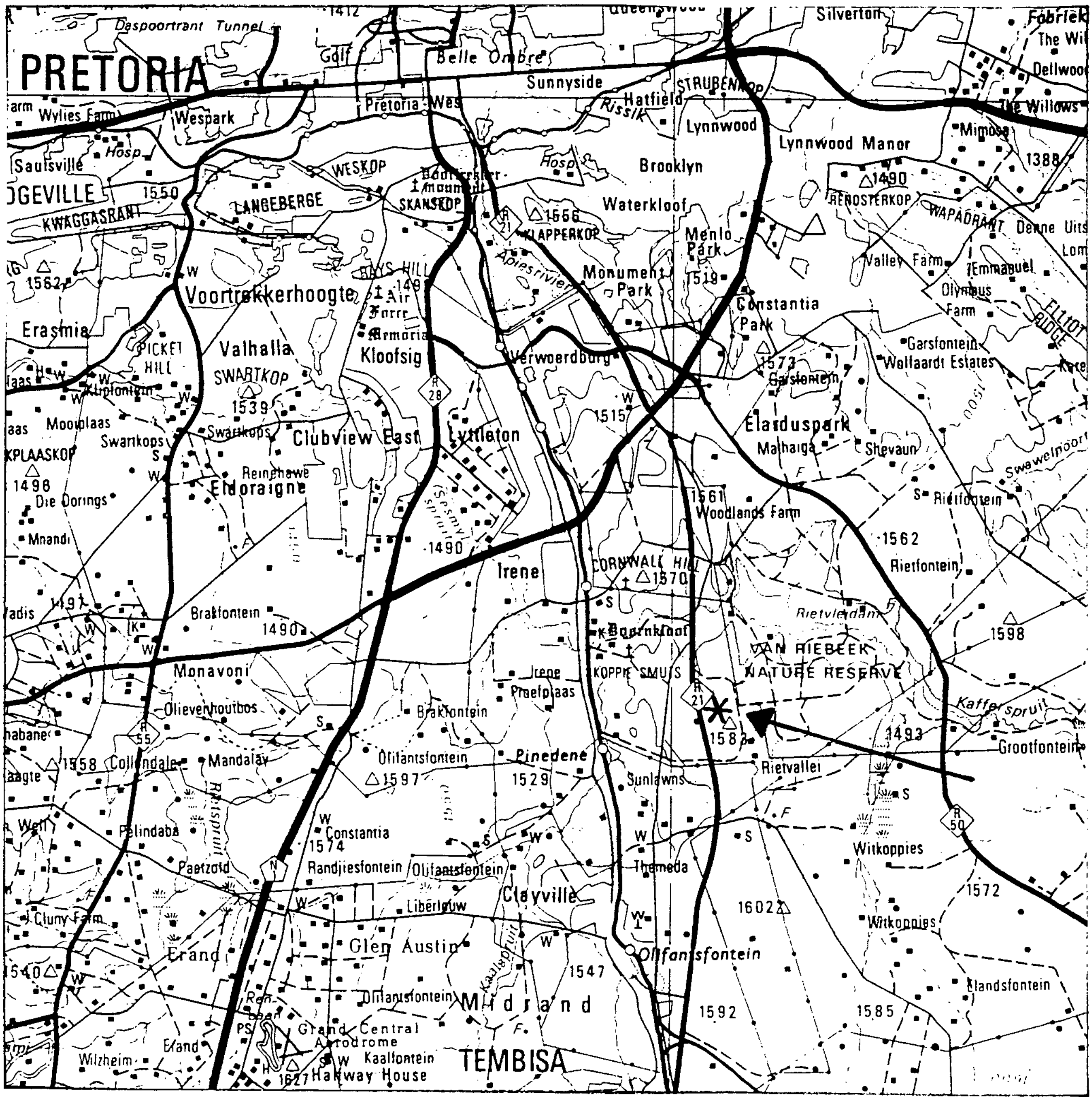
Approximate locations of the homestead of the Mathabela family in Timbavati, Gazankulu and the Wits Rural Facility



Approximate location of the Mzimhlophe Secondary School in KwaNdebele



Approximate location of Donkerhoek pig farm east of Pretoria

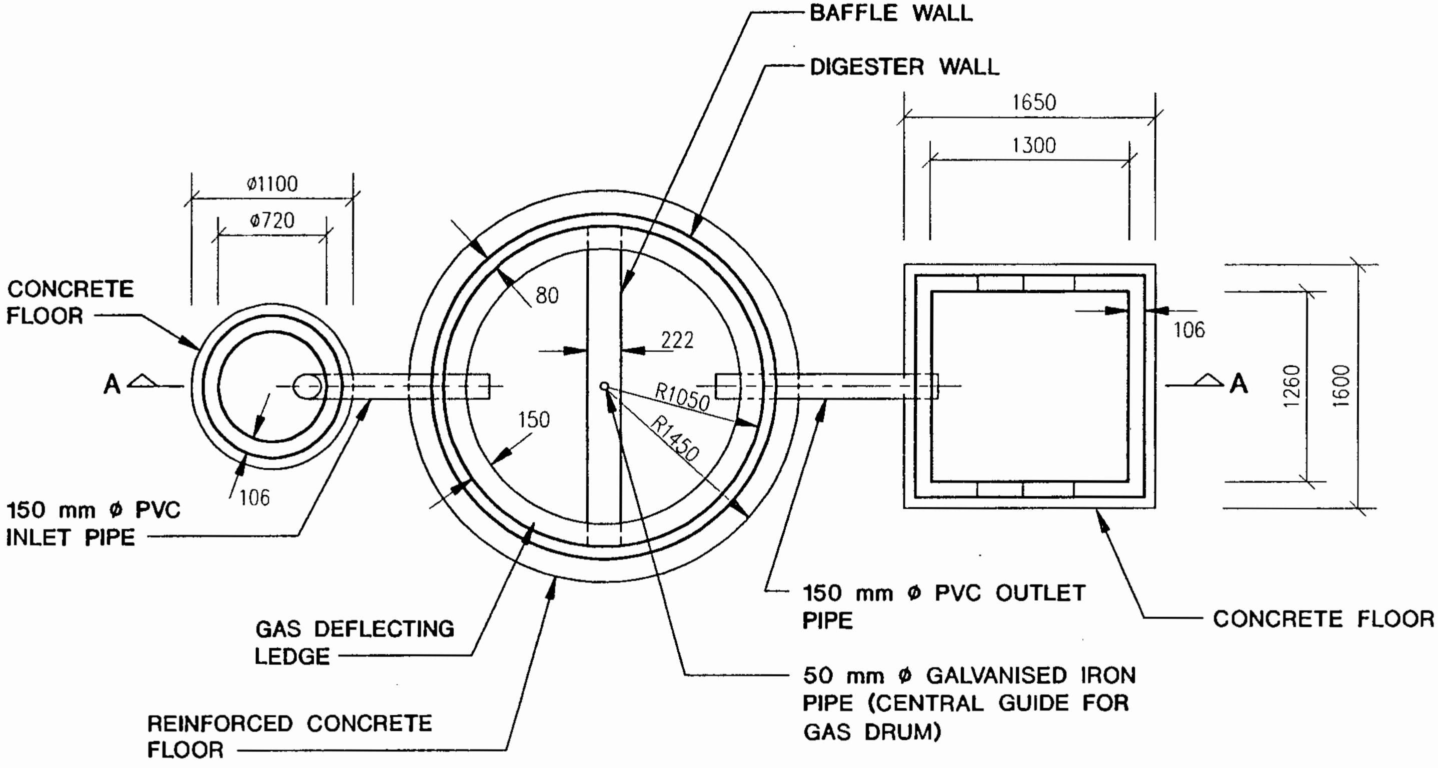


Approximate location of Doringkloof dairy south of Pretoria

Appendix B: Design drawings of pilot plants

LEGEND

- Concrete
- Ferrocement
- Bricks
- Ground level
- Compacted fill



MIXING BOX DIGESTER COLLECTION BOX

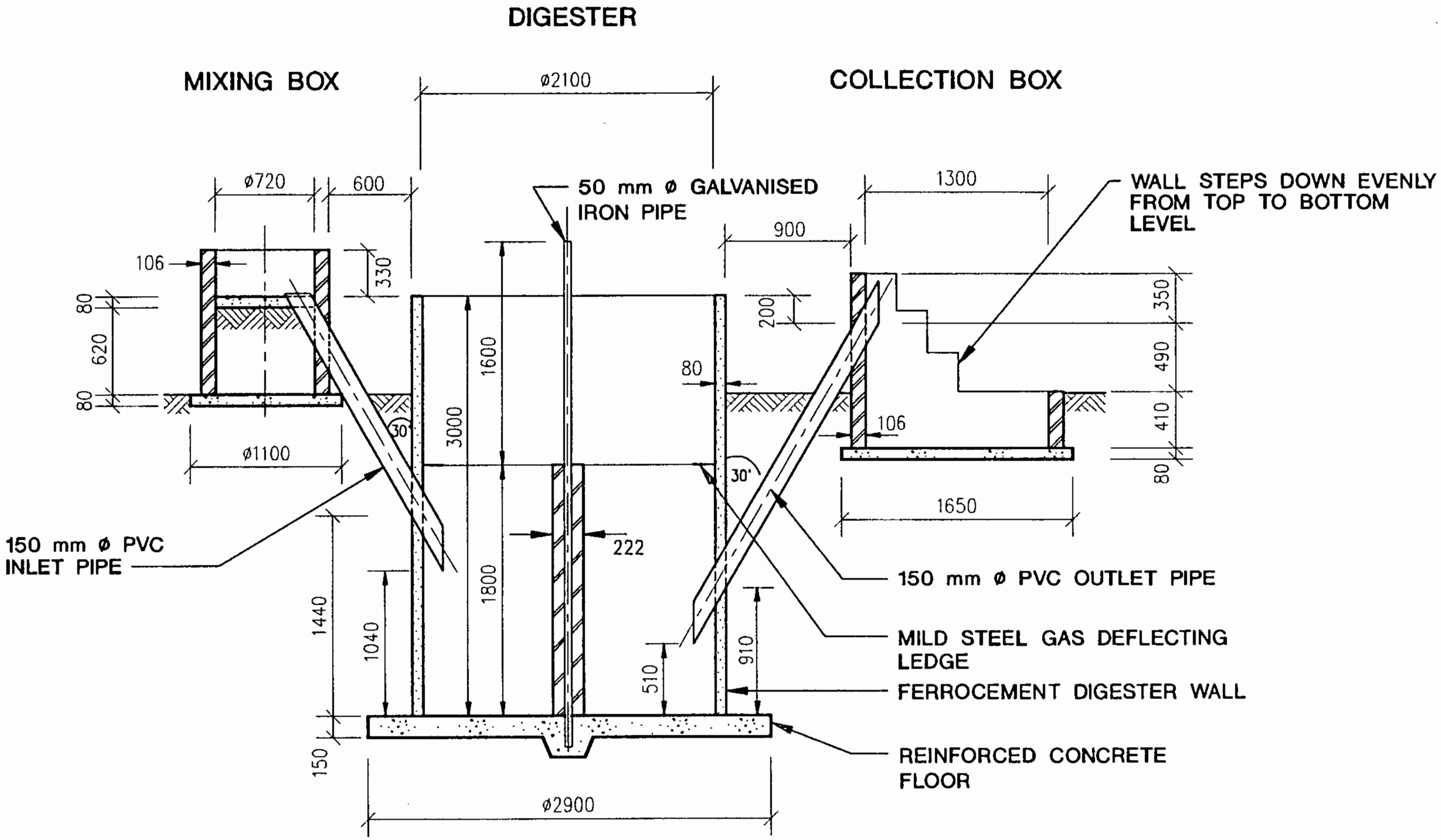
SCALE 1 : 50
dimensions in mm

PLAN

BIOGAS DIGESTER

Floating-drum biogas plant: Mathabela family

B484-5 SCALE 1=50

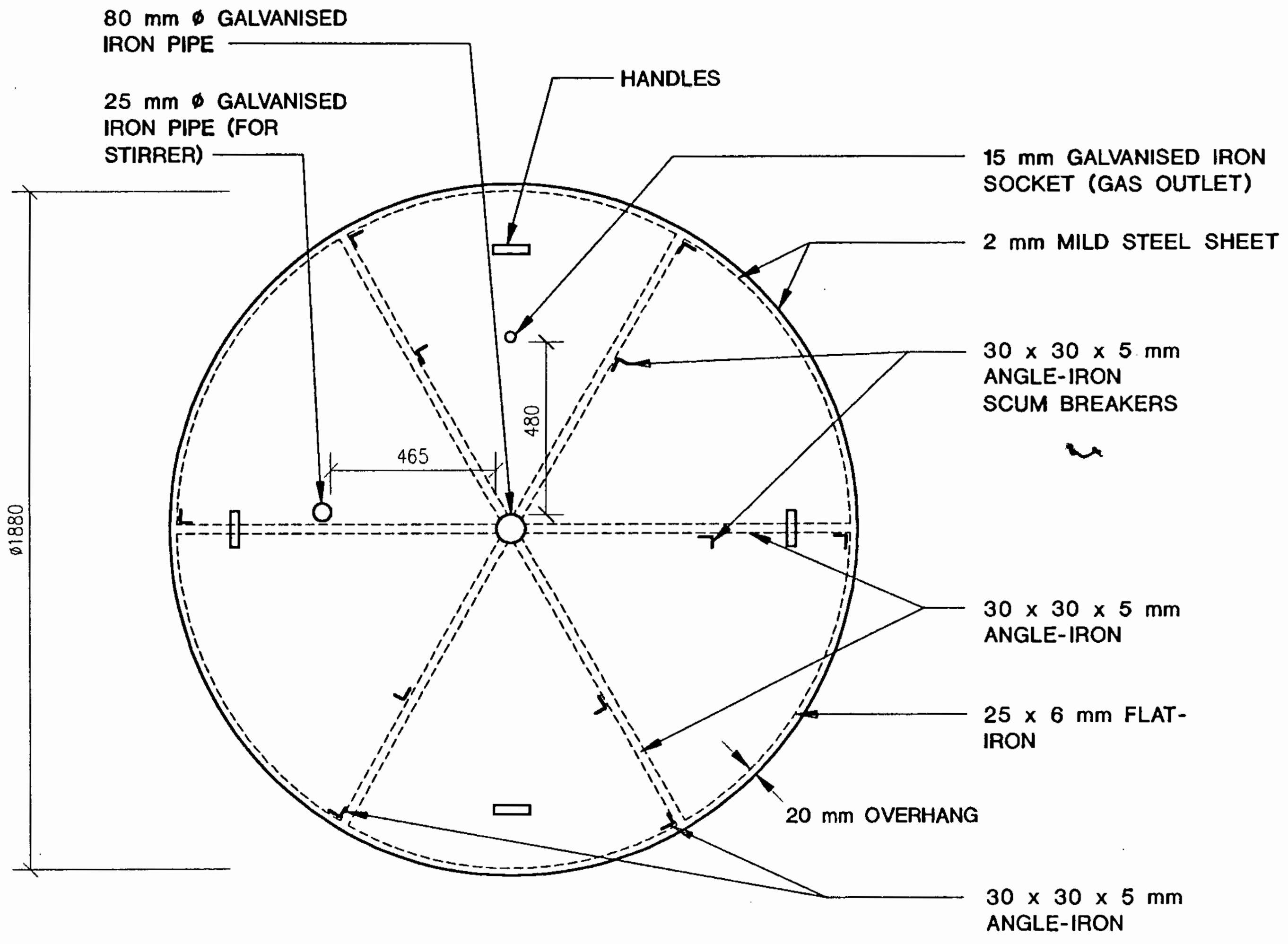


SECTION A-A

SCALE 1 : 50
dimensions in mm

BIOGAS DIGESTER

Floating-drum biogas plant: Mathabela family

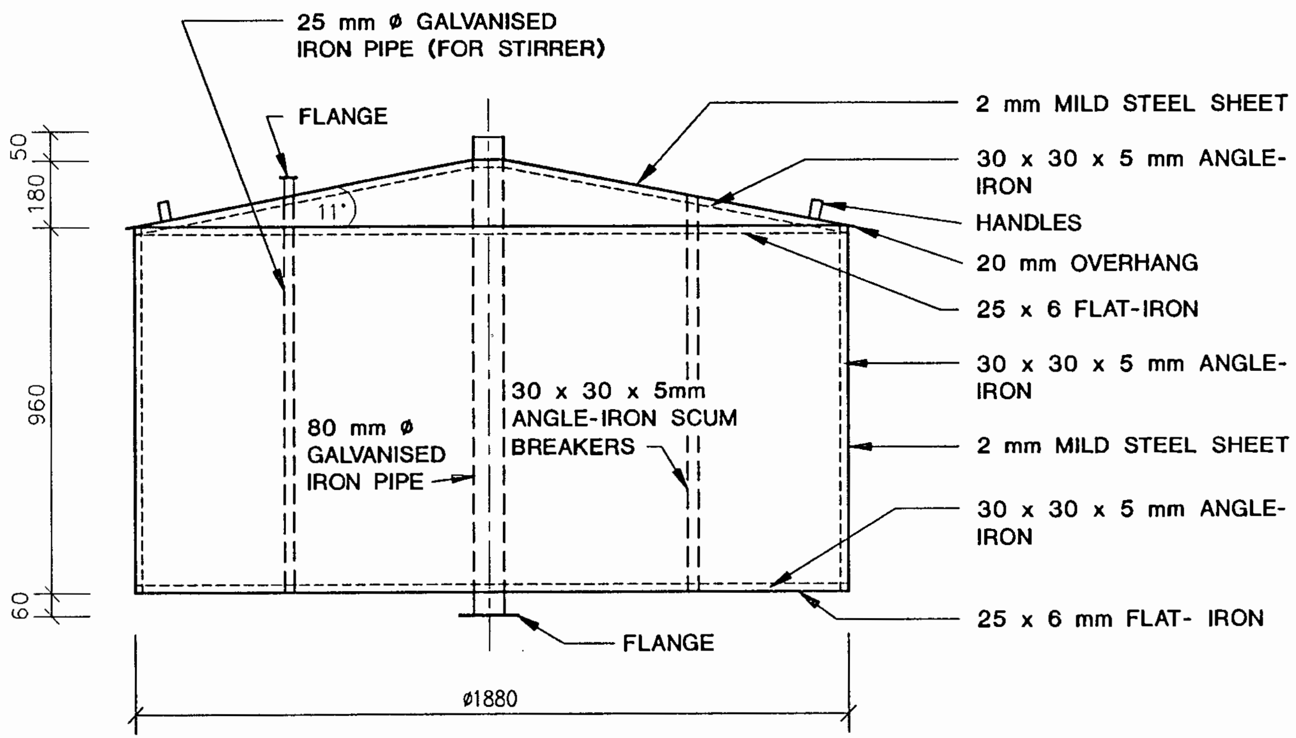


PLAN

SCALE 1 : 20
dimensions in mm

GAS DRUM

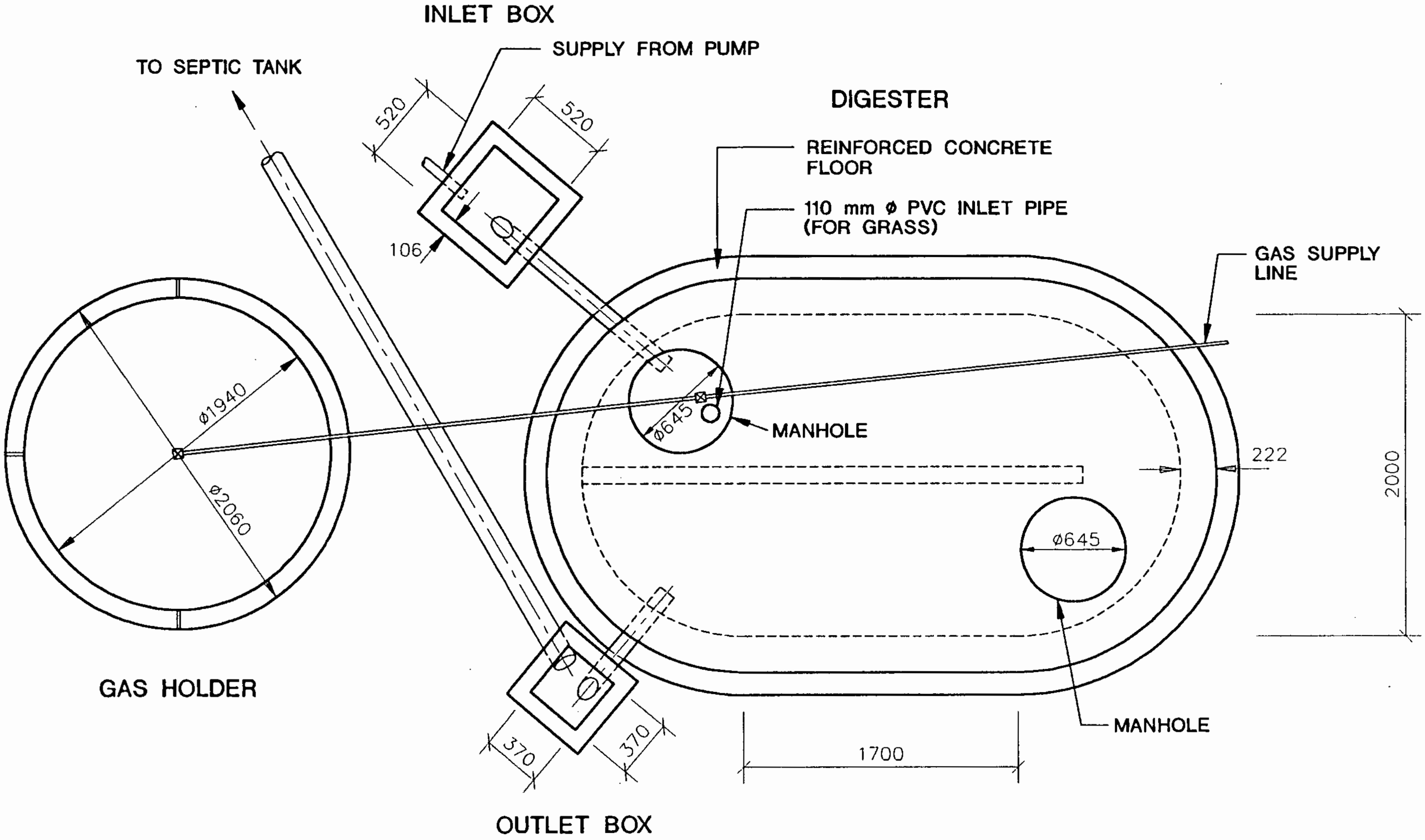
Floating-drum biogas plant: Mathabela family



SIDE ELEVATION

SCALE 1 : 20
dimensions in mm

GAS DRUM
Floating-drum biogas plant: Mathabela family



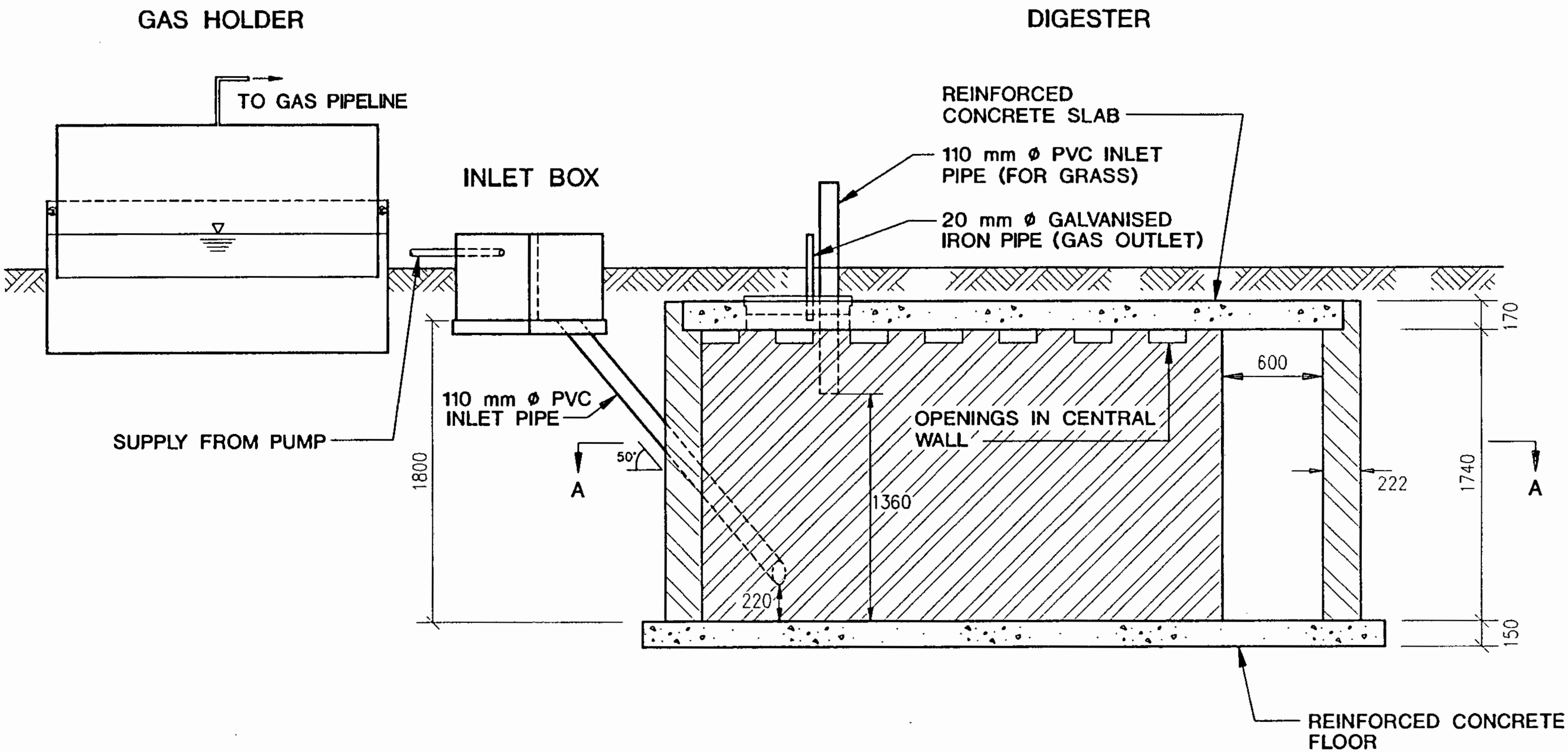
PLAN

SCALE 1 : 40
dimensions in mm

BIOGAS PLANT WITH SEPERATE GAS HOLDER

Mzimhlophe Secondary School

B484-3 SCALE 1=40

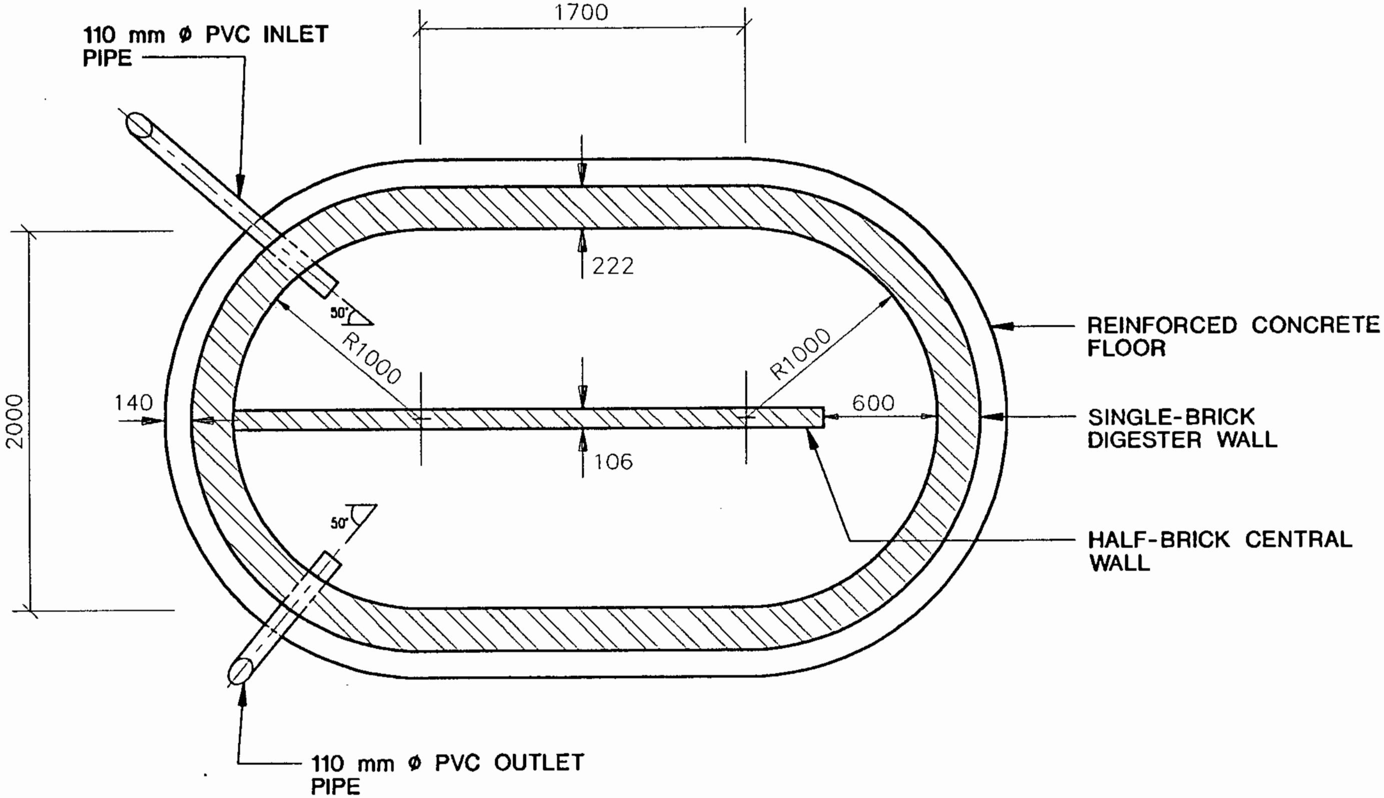


LONGITUDINAL SECTION

SCALE 1 : 40
dimensions in mm

BIOGAS PLANT WITH SEPERATE GAS HOLDER

Mzimhlophe Secondary School

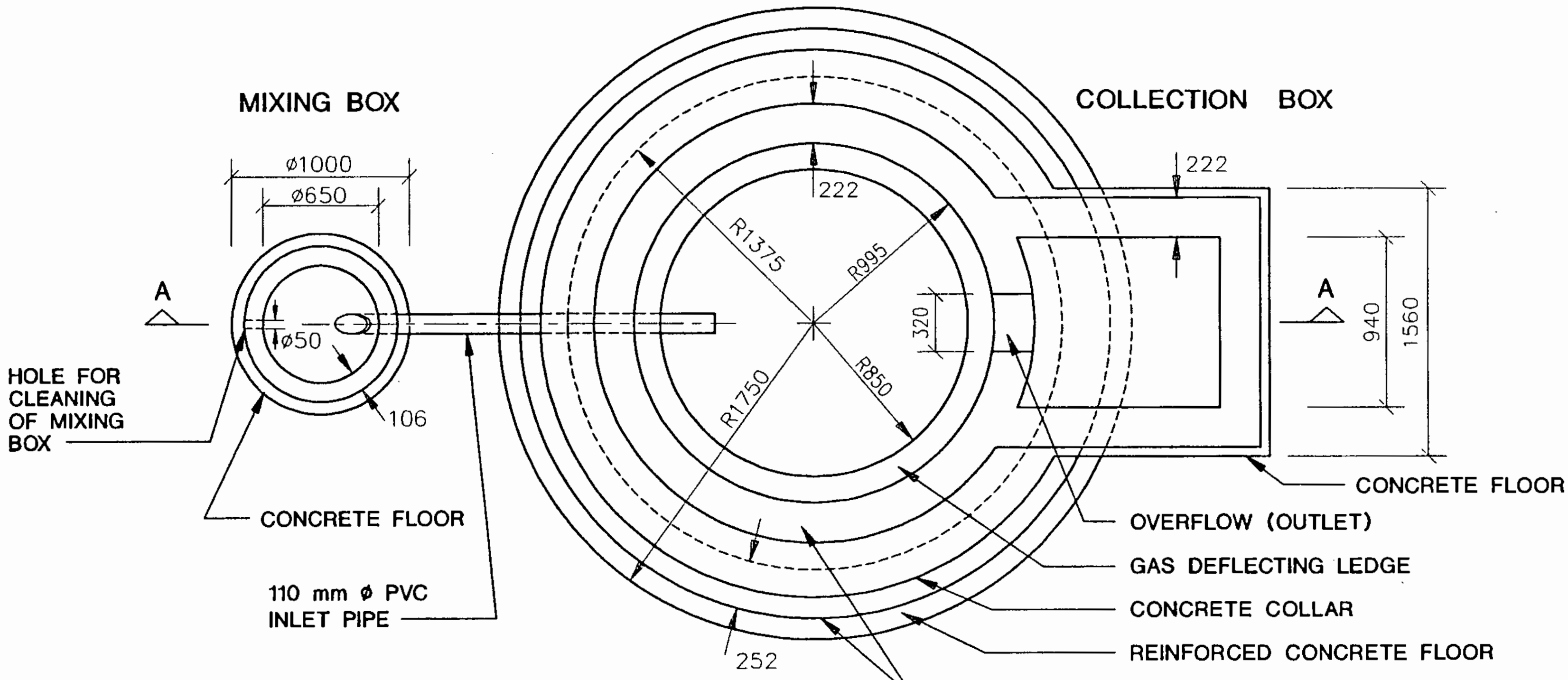


SECTION A-A

SCALE 1 : 40
dimensions in mm

BIOGAS DIGESTER

Biogas plant with separate gas holder:
Mzimhlophe Secondary School



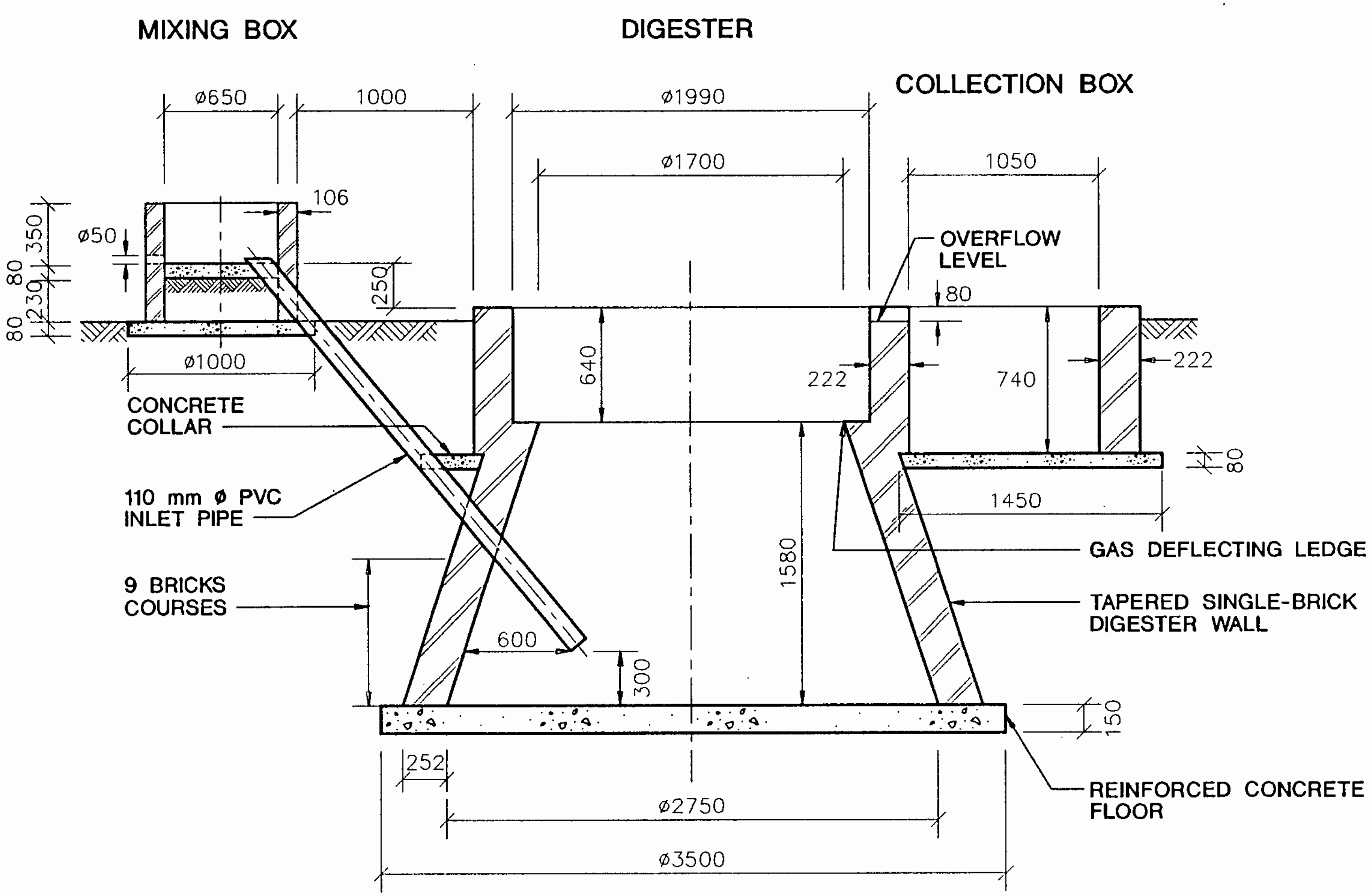
PLAN

SCALE 1 : 40
dimensions in mm

BIOGAS DIGESTER

Floating-drum biogas plant: University of Pretoria

B484-9 SCALE 1=40

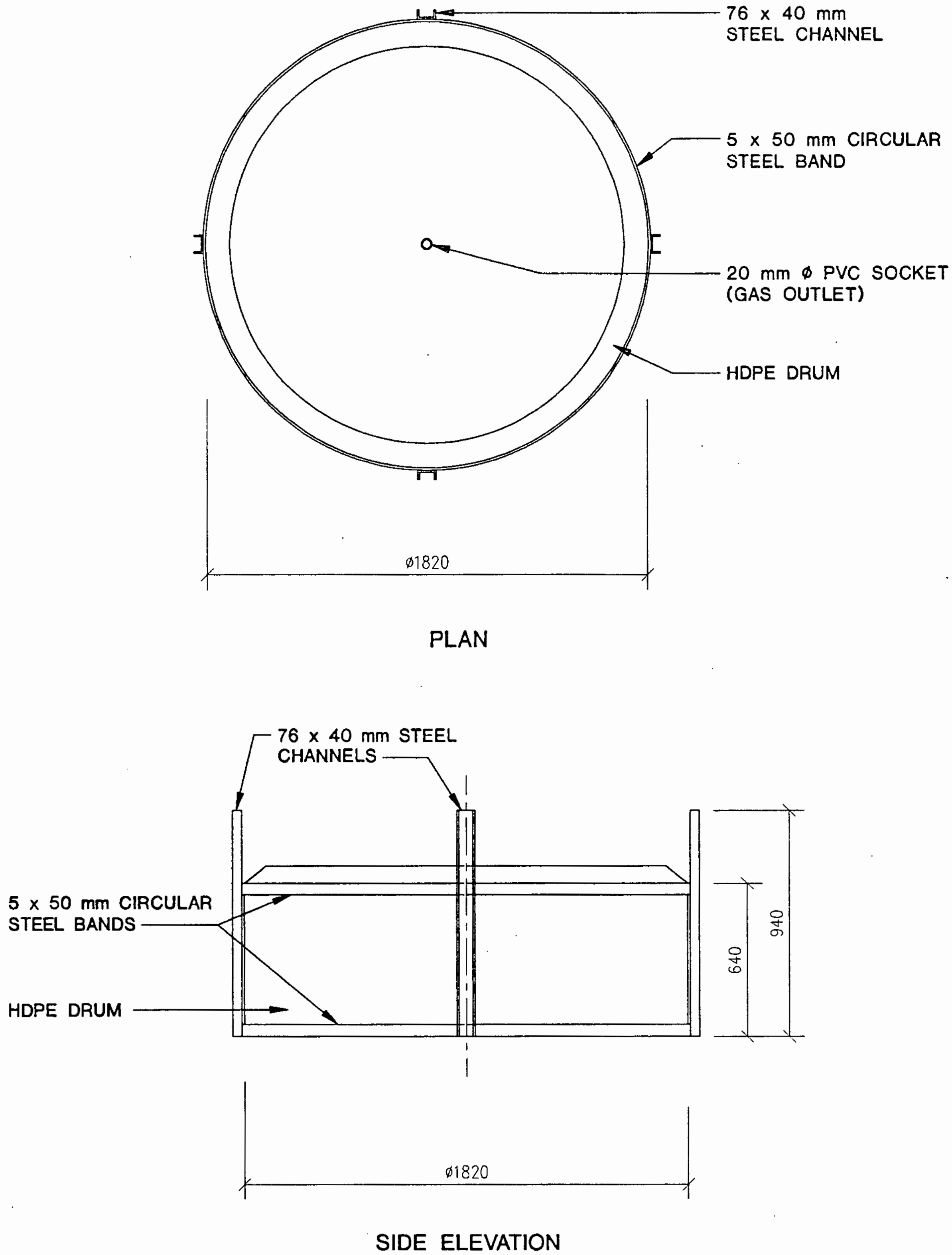


SECTION A-A

SCALE 1 : 40
dimensions in mm

BIOGAS DIGESTER

Floating-drum biogas plant: University of Pretoria



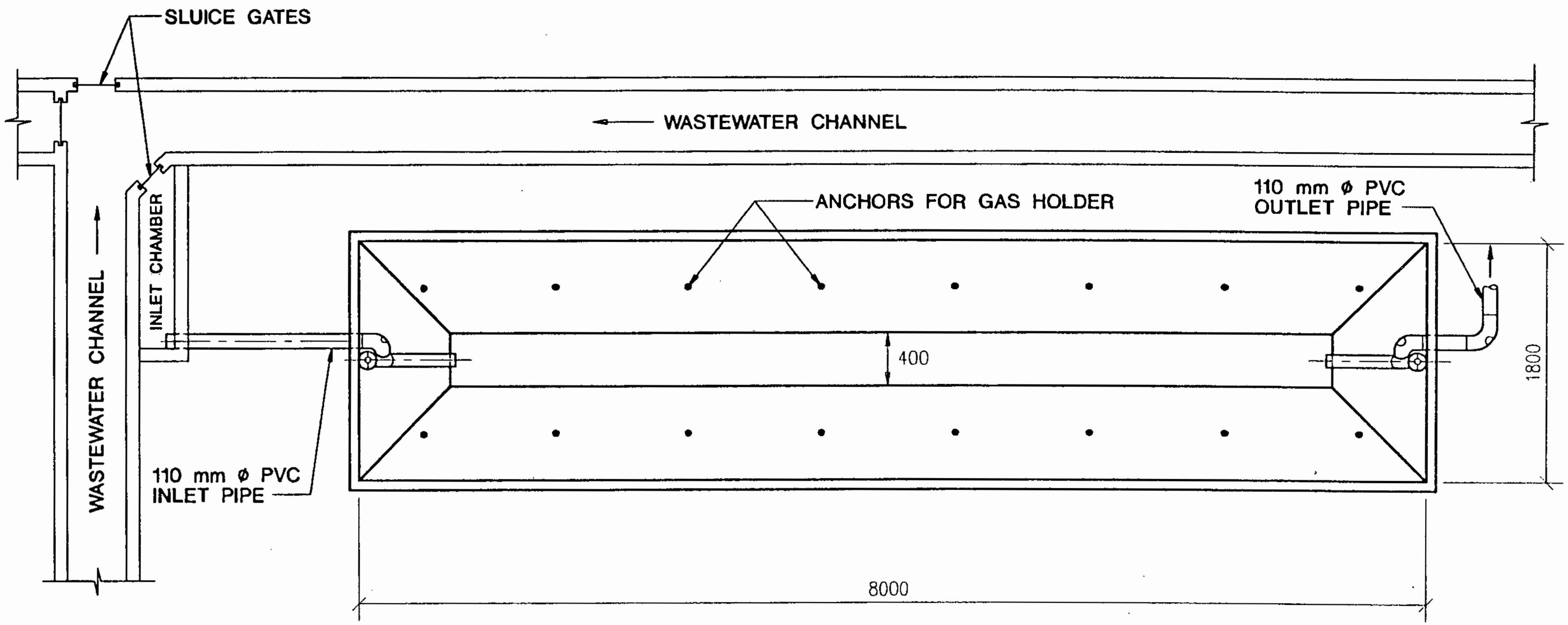
SCALE 1 : 25
dimensions in mm

GAS DRUM

Floating-drum biogas plant: University of Preto

B484-1 SCALE 1=25

B484-13 SCALE 1=50



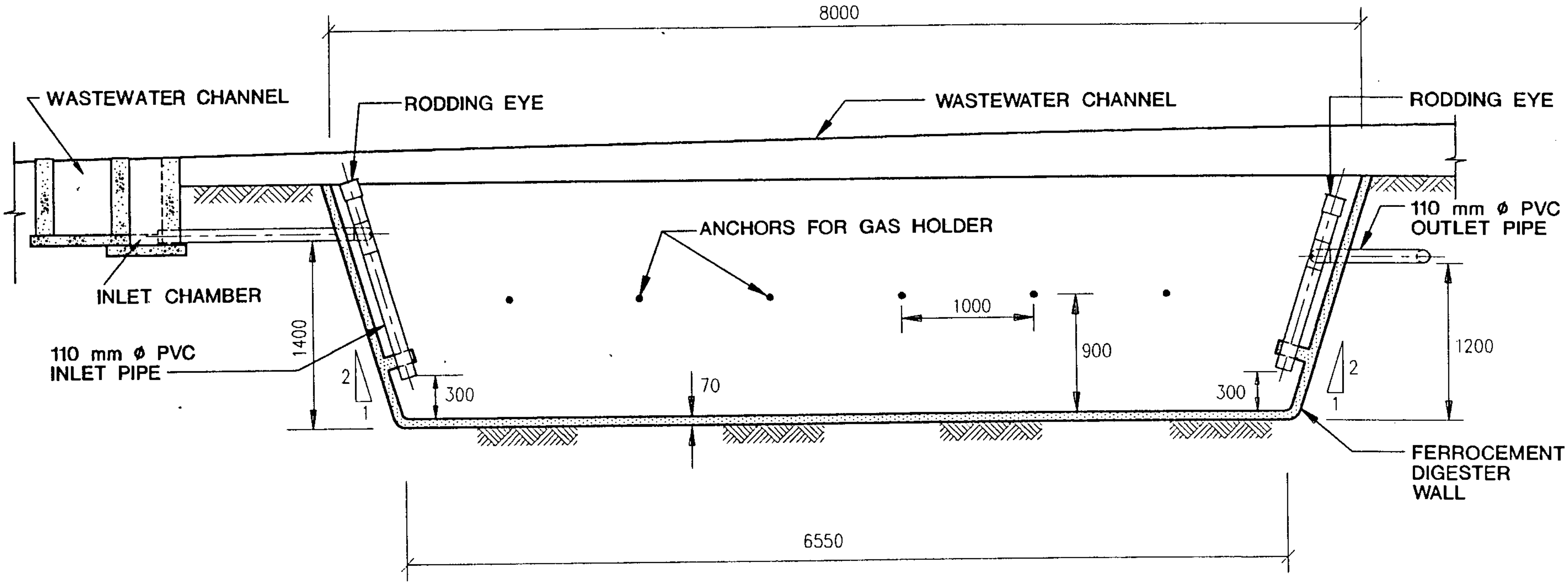
PLAN

SCALE 1 : 50
dimensions in mm

BIOGAS DIGESTER

Flexible cover biogas plant: Donkerhoek pig farm

B484-12 SCALE 1=50

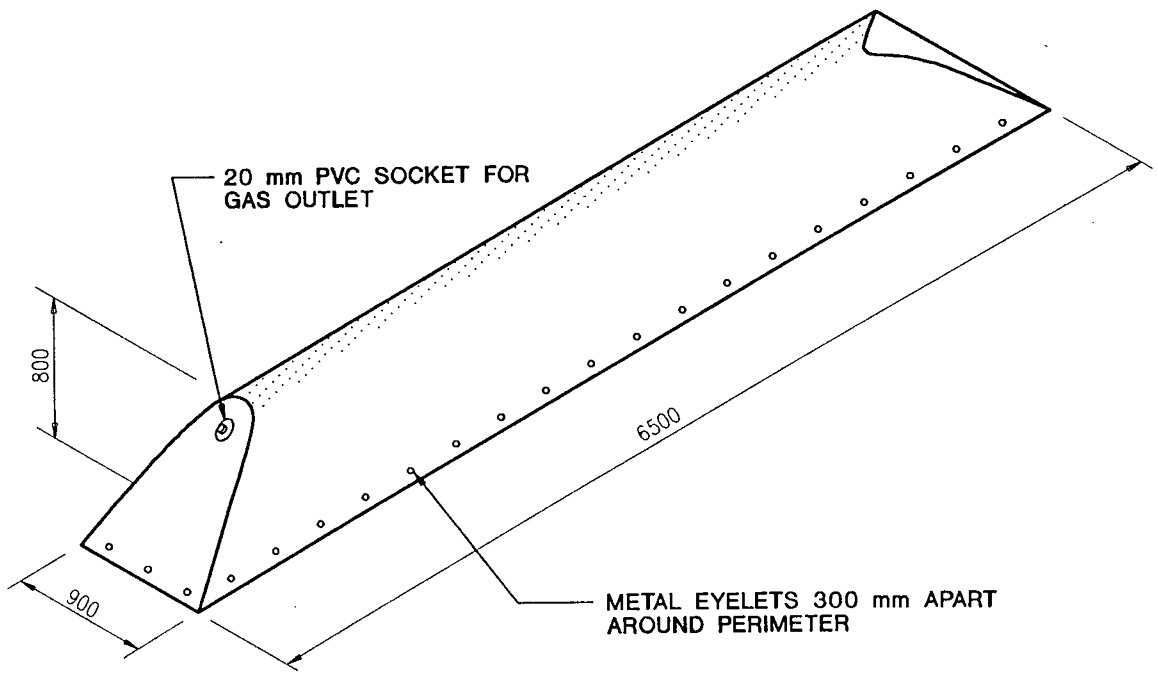


LONGITUDINAL SECTION

SCALE 1 : 50
dimensions in mm

BIOGAS DIGESTER

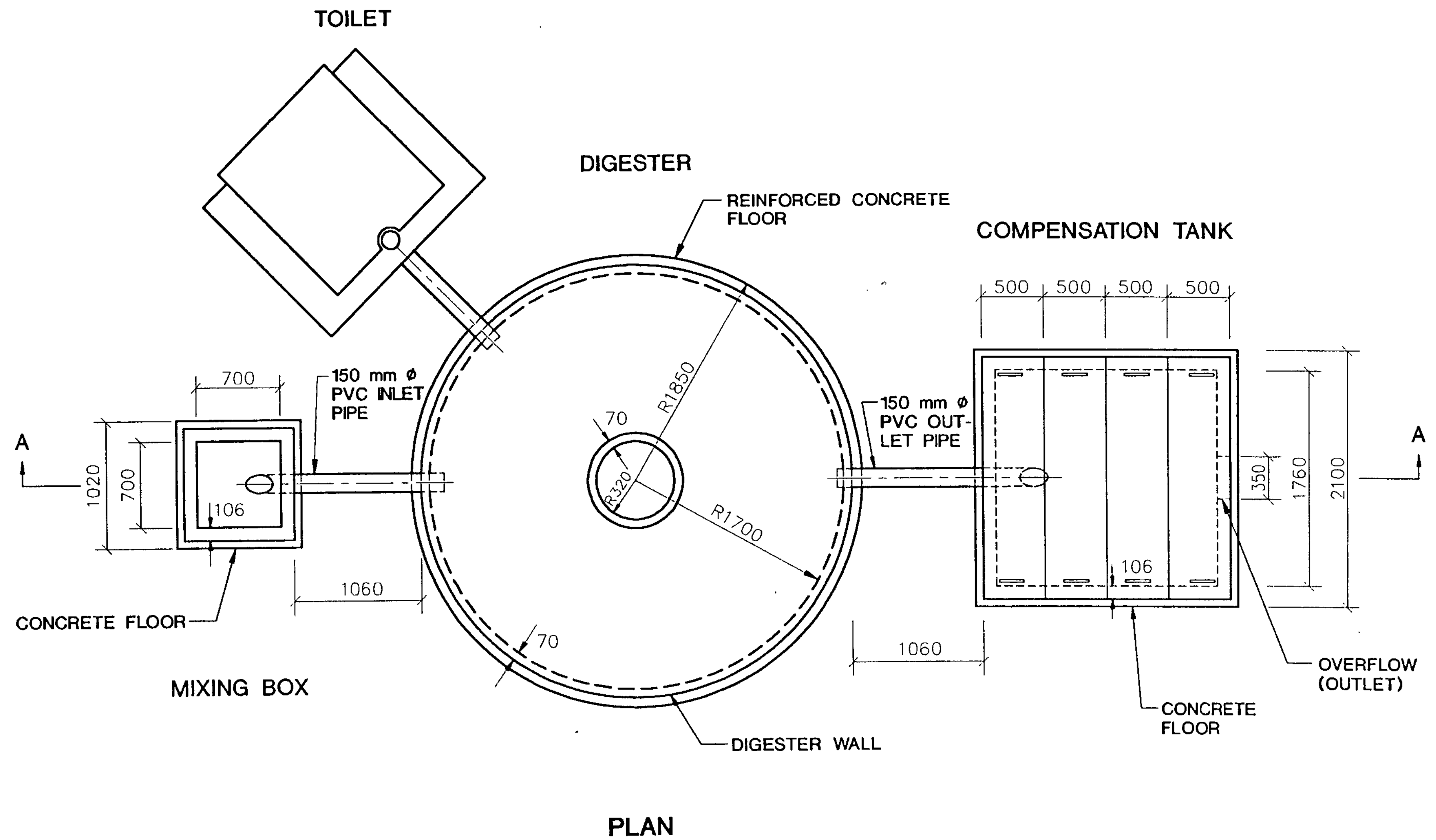
Flexible cover biogas plant: Donkerhoek pig farm



SCALE 1 : 50
dimensions in mm

GAS HOLDER

**Flexible cover biogas plant:
Donkerhoek pig farm**

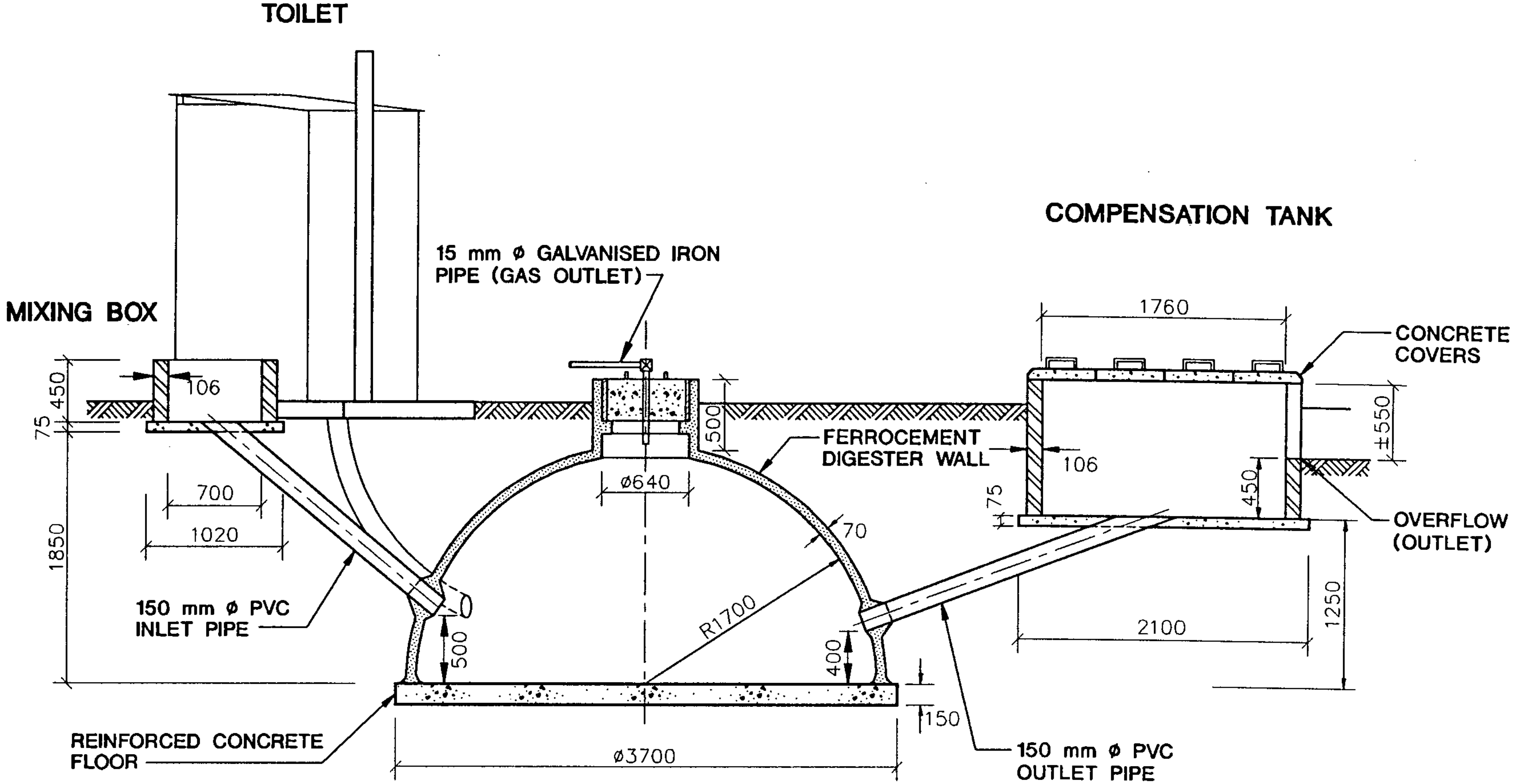


SCALE 1 : 50
dimensions in mm

FIXED-DOME BIOGAS PLANT

Doringkloof Diary

B484-16 SCALE 1=50



SECTION A-A

SCALE 1 : 50
dimensions in mm

FIXED-DOME BIOGAS PLANT

Doringkloof Diary

Appendix C: Photographs of pilot plants

Figure C.1: The floating-drum biogas plant that was built at the homestead of the Mathabela family in Gazankulu.

Figure C.2: The galvanised iron mould used to build the ferrocement digester at the homestead of the Mathabela family.

Figure C.3: The biogas digester that was installed at the Mzimhlophe Secondary School in KwaNdebele.

Figure C.4: The biogas digester at the school being filled by the tanker which served the septic tank at the school. The separate gas holder and the control box for the pumping system are also shown.

Figure C.5: **The floating-drum biogas plant that was installed at the University of Pretoria's experimental farm.**

Figure C.6: **The modified biogas plant at the experimental farm with the HDPE gas drum and the new guiding system for the drum.**

Figure C.7: The gas burners that were installed in the kitchen rondavel of the Mathabela family. Mr Mathabela is shown here with the burners.

Figure C.8: Locally available gas burners that were tested at the biogas plant at the University of Pretoria's experimental farm.

Figure C.9: The flexible cover biogas plant that was installed at Donkerhoek piggery east of Pretoria.

Figure C.10: The flexible cover plant with the new gas holder, and the weights that were placed on the gas holder to increase the gas pressure.

Figure C.12: **The fixed-dome biogas plant with the ferrocement digester that was built at Doringkloof dairy south of Pretoria.**

Appendix D: Maps of climatic zones

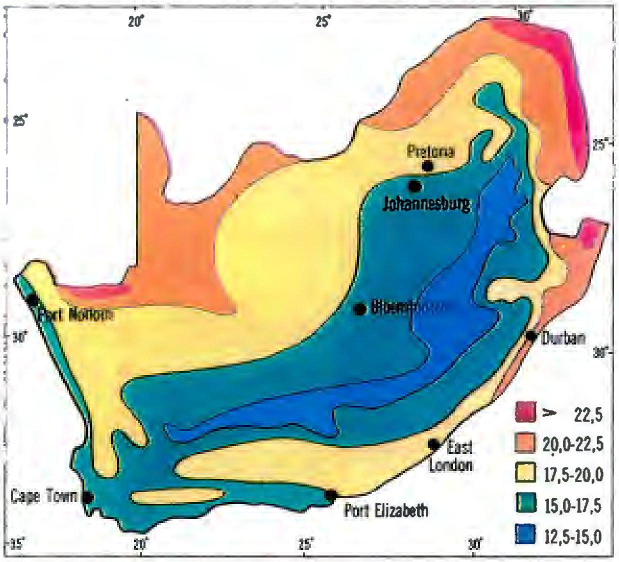


Figure D.1: **Mean annual surface temperatures in South Africa. (Department of Water Affairs 1986: 1.6)**

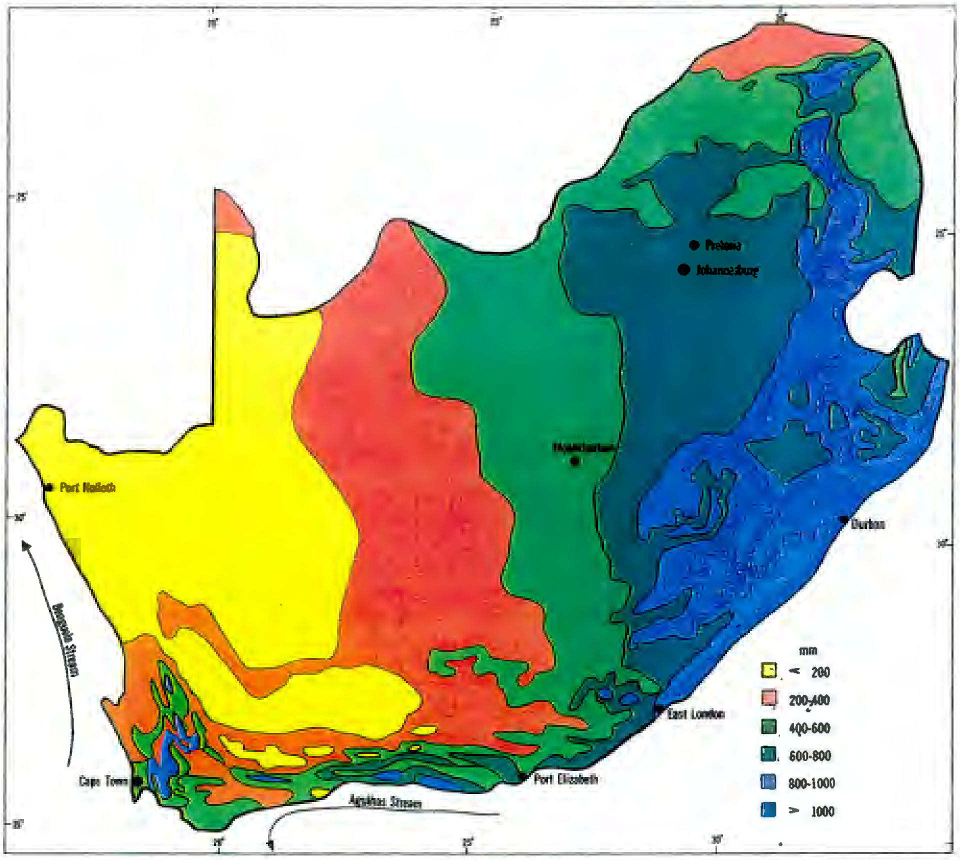
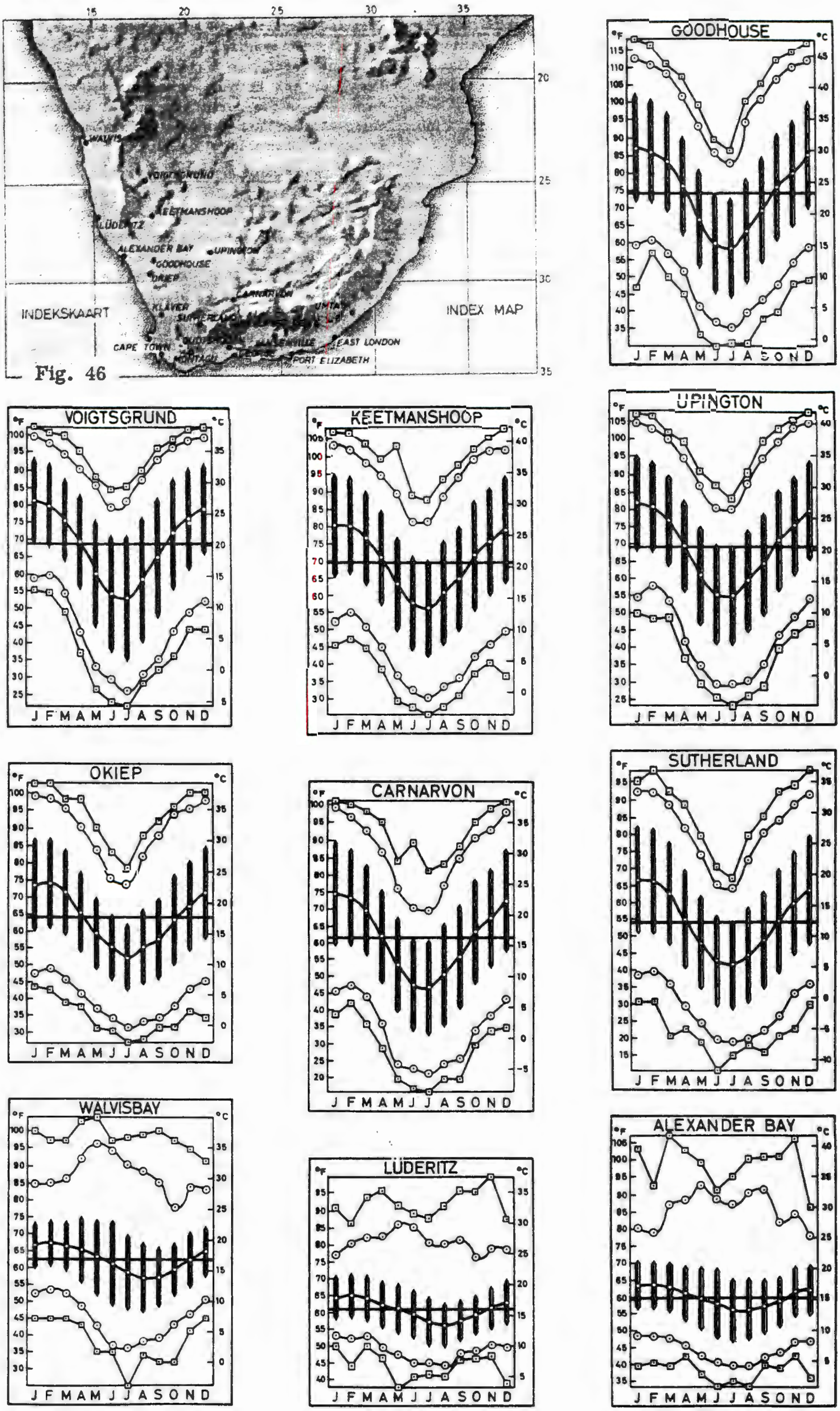


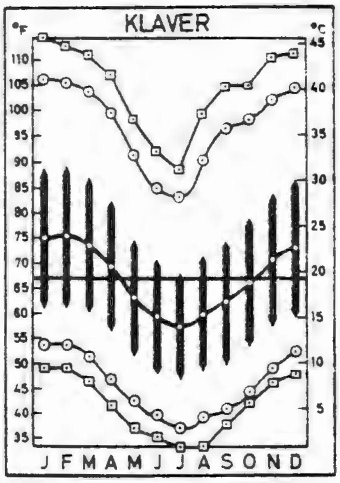
Figure D.2: **Mean annual rainfall in South Africa. (Department of Water Affairs 1986: 1.4)**

Appendix E: Atmospheric temperatures at various locations in South Africa (Schulze 1986: 86-91)



INDEKSKAART
INDEX MAP
WALVIS
KEETMANSHOOP
ALEXANDER BAY
UPINGTON
GOODHOUSE
CAPE TOWN
EAST LONDON
PORT ELIZABETH
GOODHOUSE
VOIGTSGRUND
KEETMANSHOOP
UPINGTON
OKIEP
CARNARVON
SUTHERLAND
WALVISBAY
LÜDERITZ
ALEXANDER BAY
°F
°C
J F M A M J J A S O N D

Fig. 46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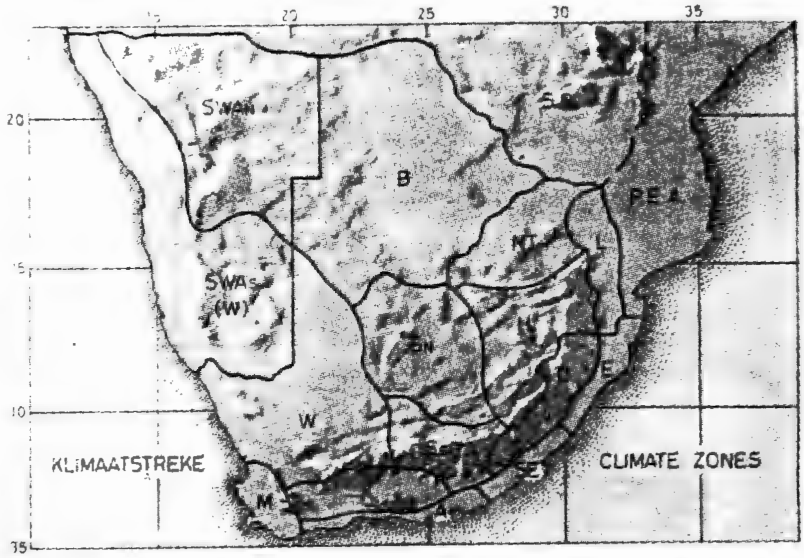
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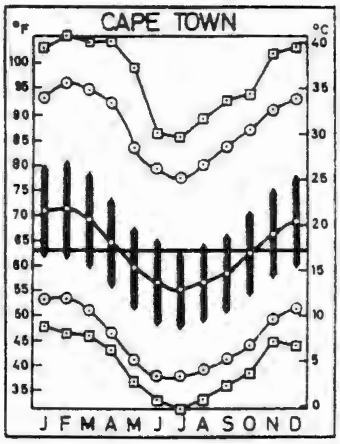
CLIMATE ZONES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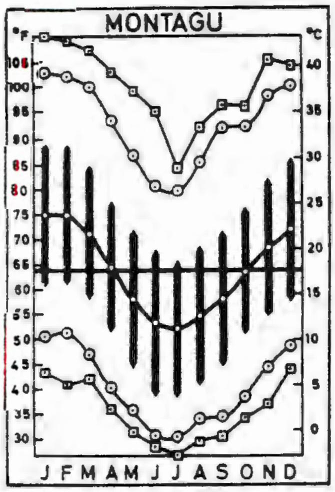
°F
°C
J F M A M J J A S O N D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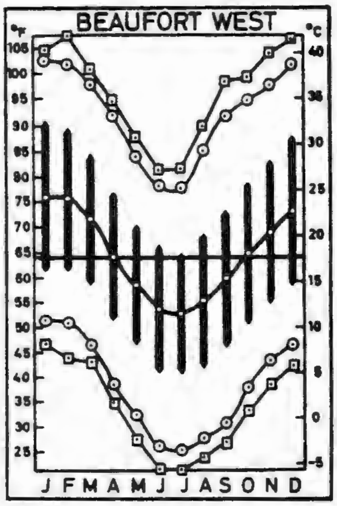
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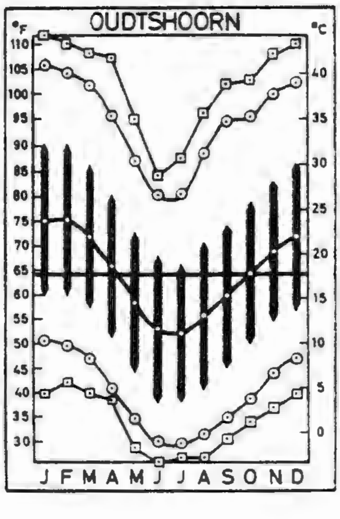
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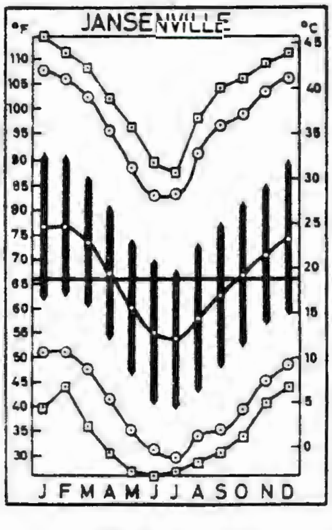
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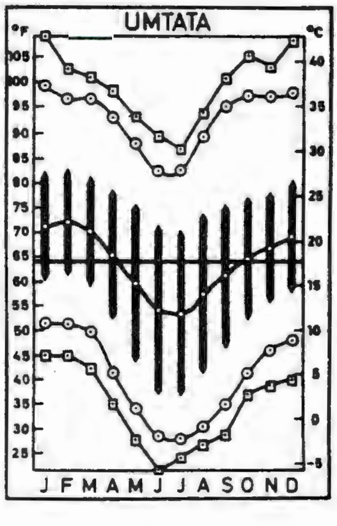
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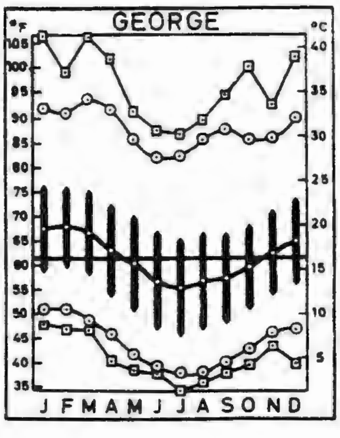
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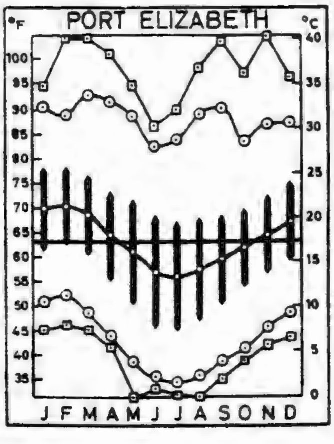
PORT ELIZABETH
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°C
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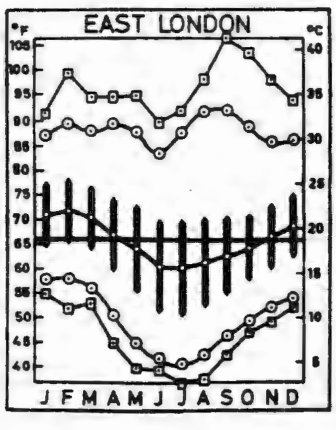
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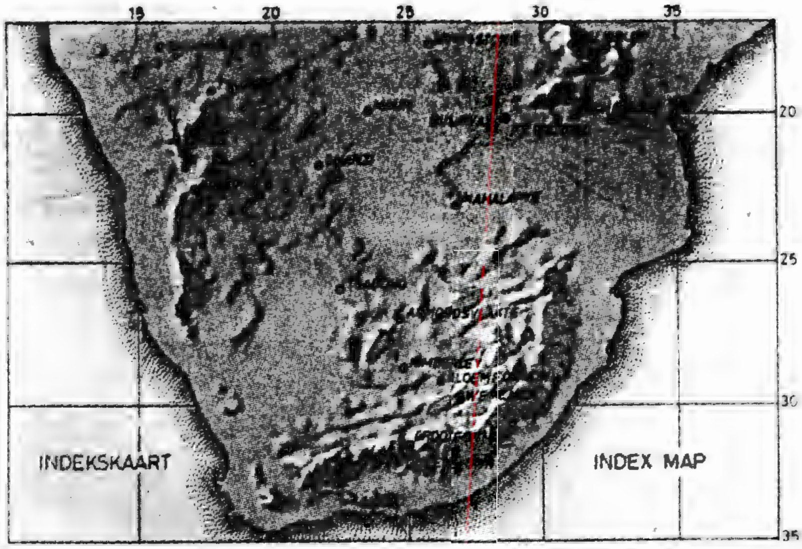
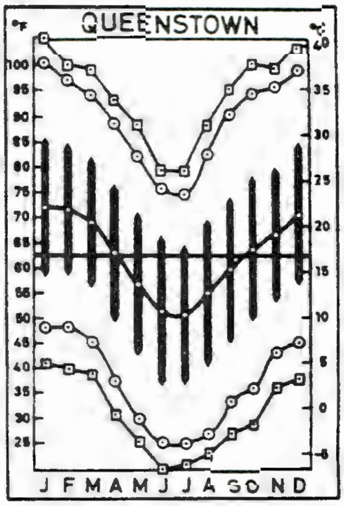

INDEKSKAART
INDEX MAP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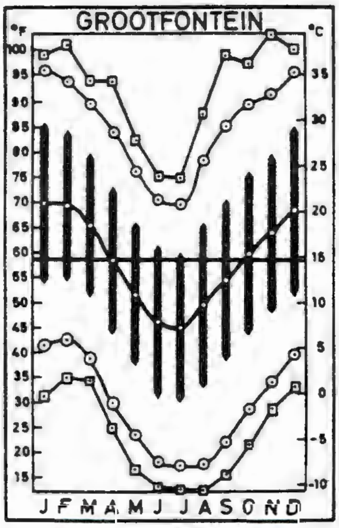
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°C
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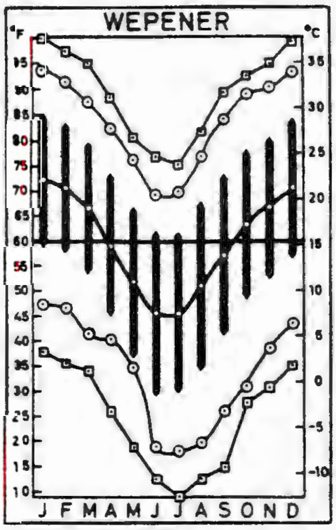
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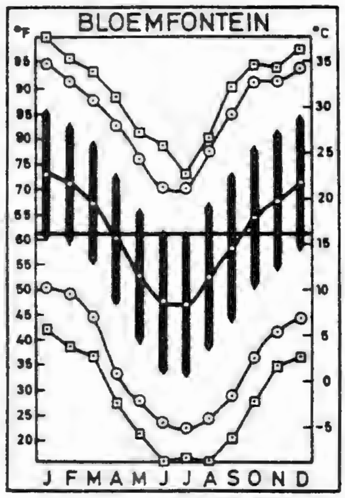
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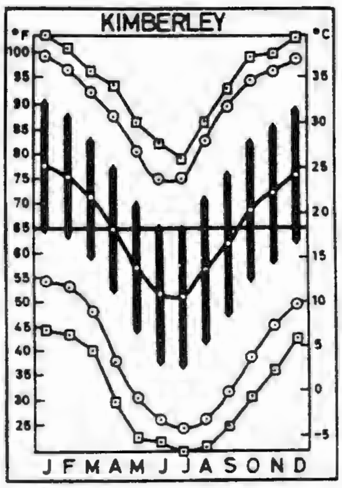
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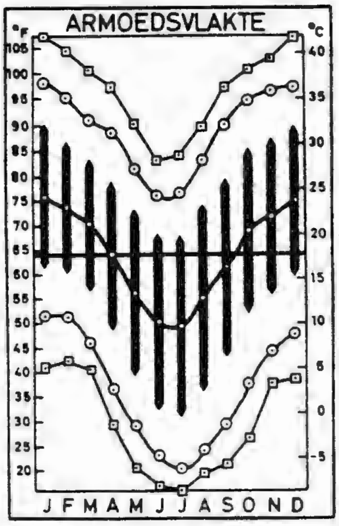
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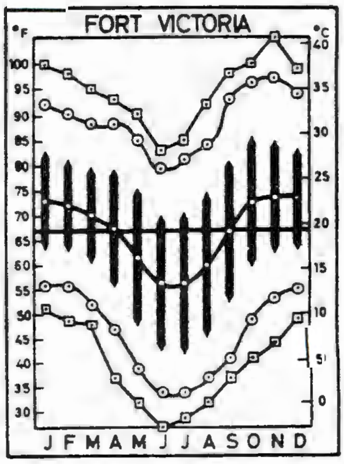
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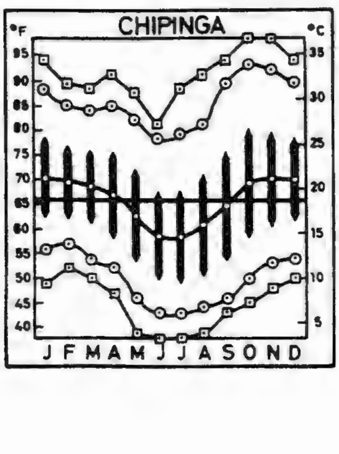
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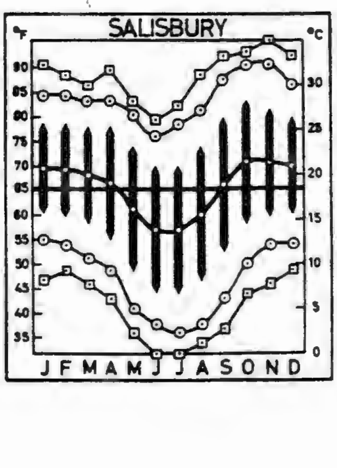
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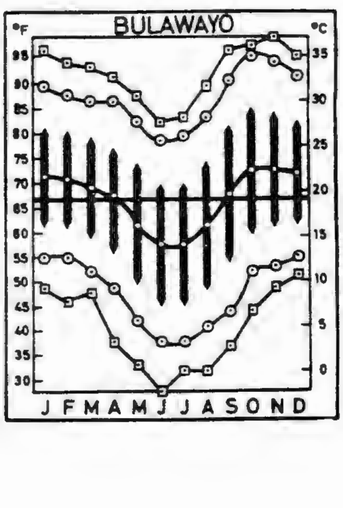
J F M A M J J A S O N D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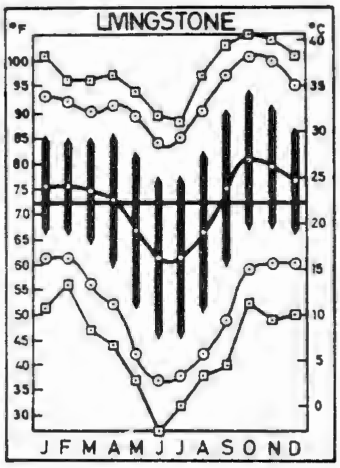
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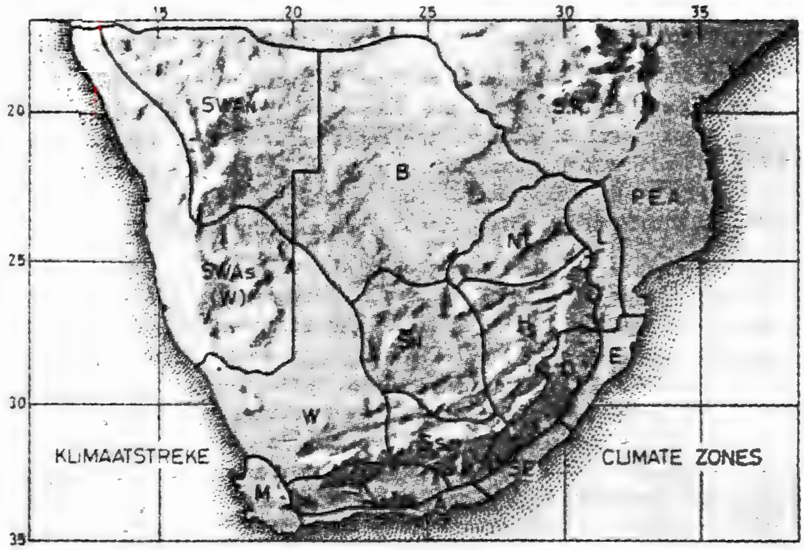
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SR
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PEA
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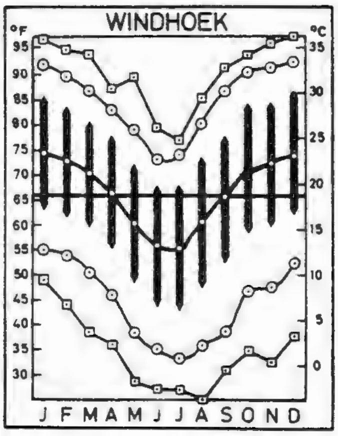
L
SWAs (W)
SH
H
E
W
KLIMAATSTREKE
CLIMATE ZONES
M
SE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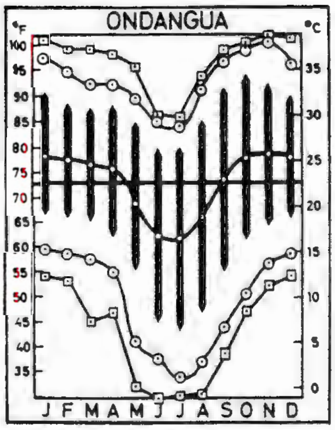
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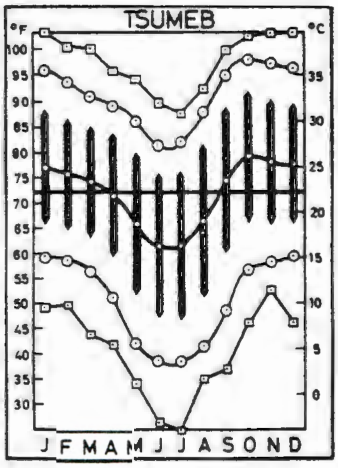
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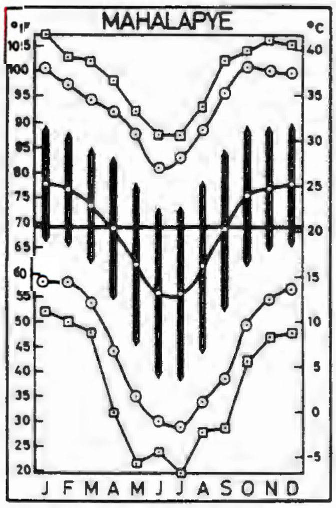
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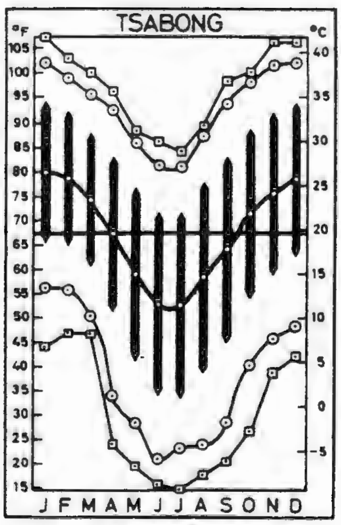
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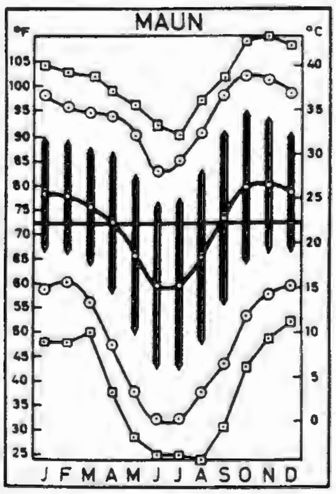
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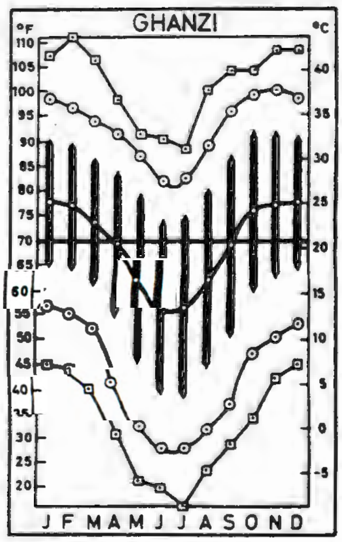
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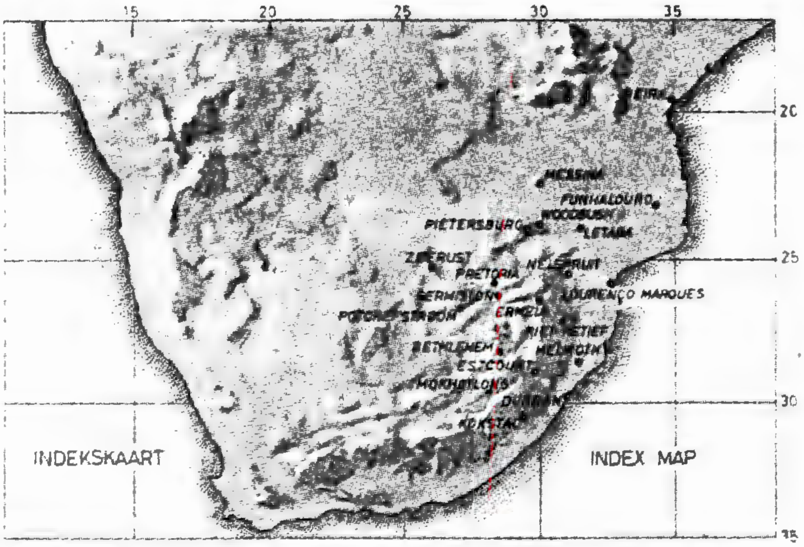
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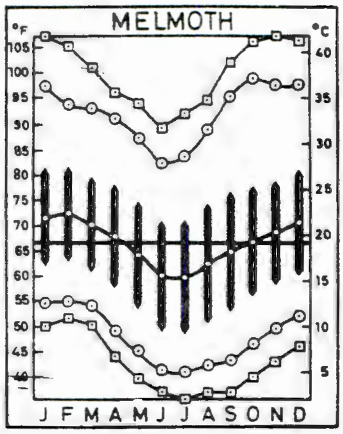
BEIRA
MESSINA
FUNHALOURO
WOODBUSH
LETABA
PIETERSBURG
ZEERUST
PRETORIA
NELSPRUIT
GERMISTON
LOURENCO MARQUES
POTCHEFSTROOM
ERMELO
PIET RETIEF
BETHLEHEM
MELMOTH
ESTCOURT
MOKHOTLONG
DURBAN
KOKSTAD
INDEKSKAART
INDEX MAP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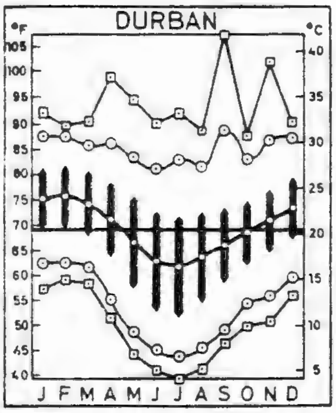
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°C
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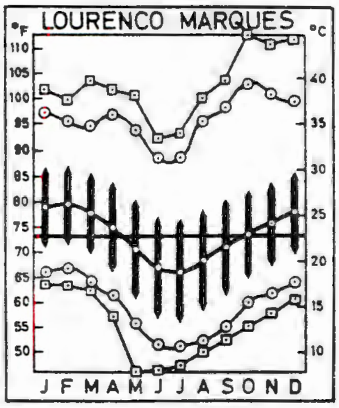
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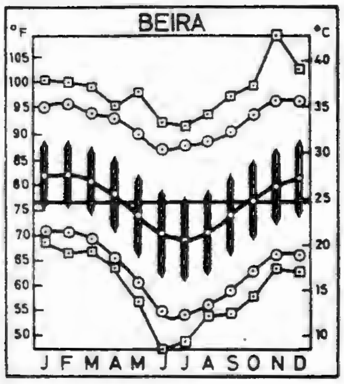
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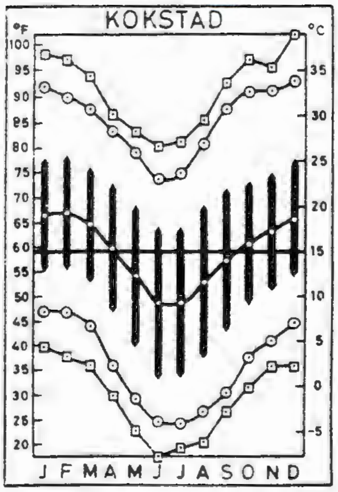
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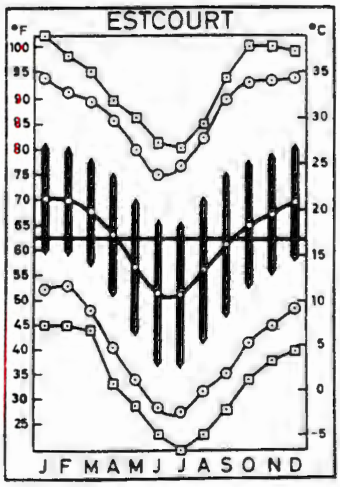
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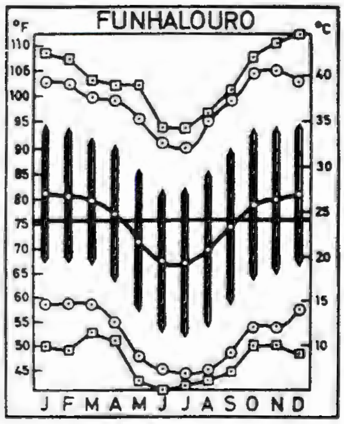
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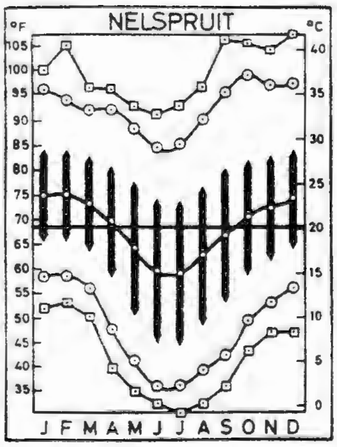
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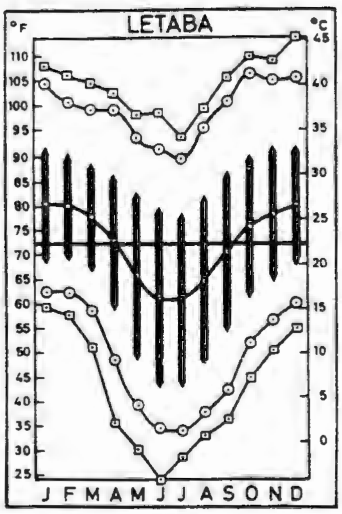
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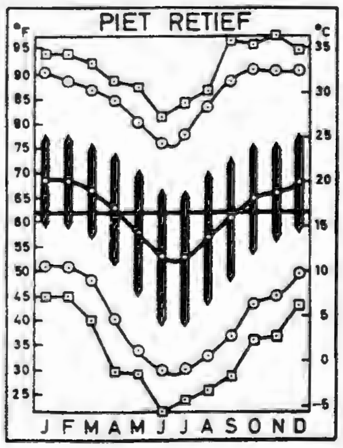
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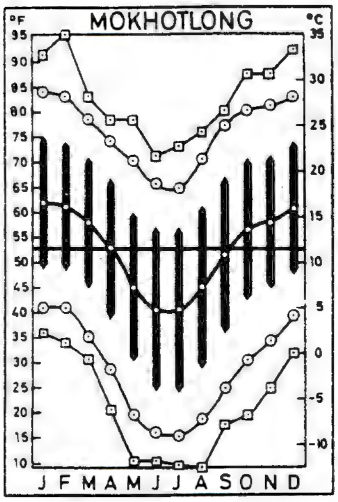
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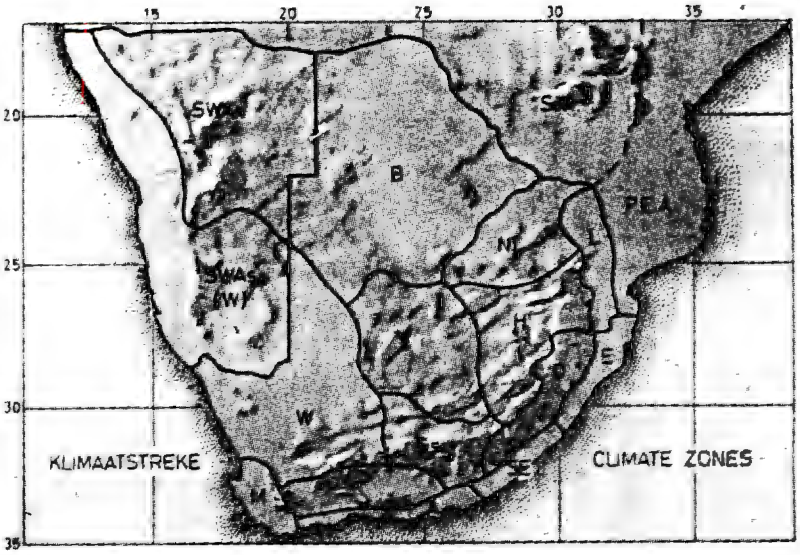
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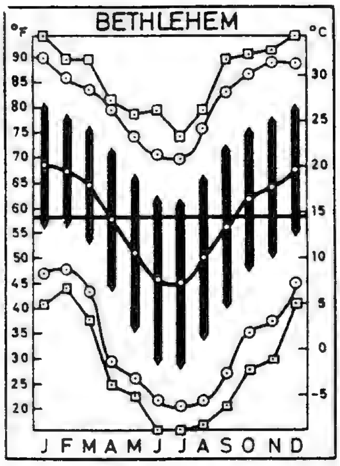
KLIMAATSTREKE
CLIMATE ZONES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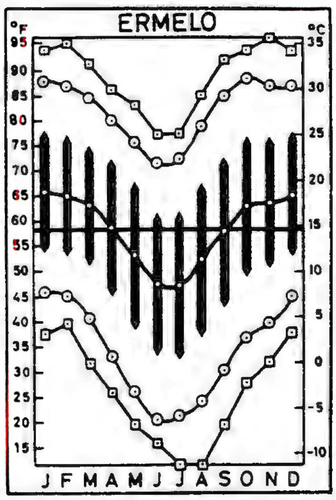
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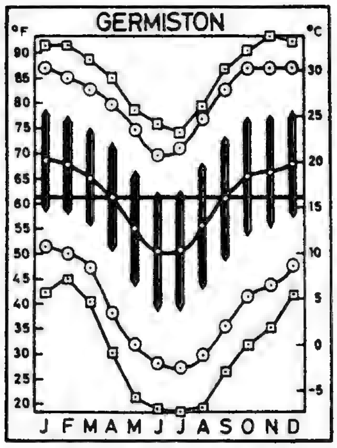
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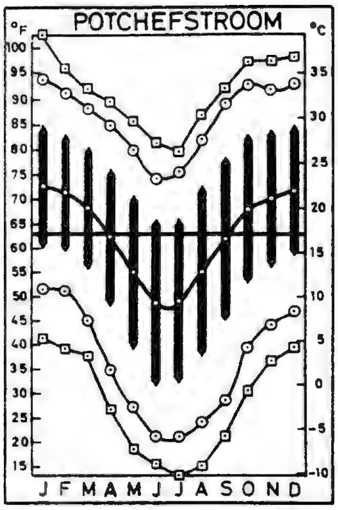
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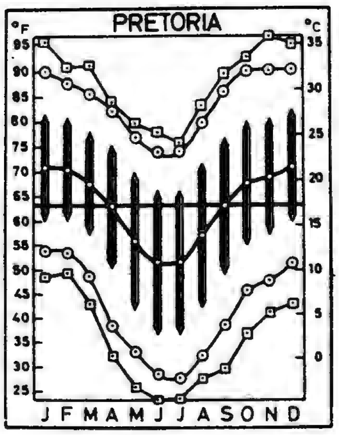
°C
J F M A M J J A S O N D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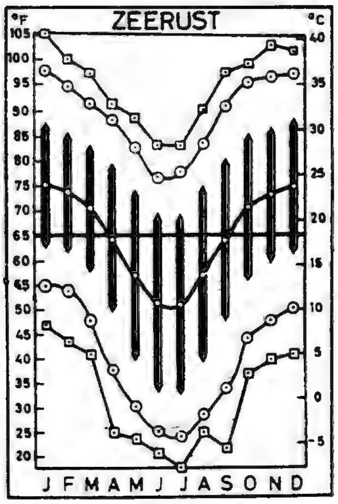
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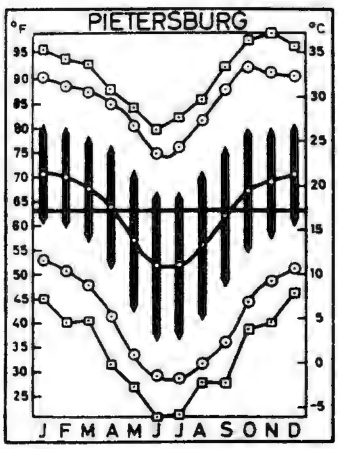
°C
J F M A M J J A S O N D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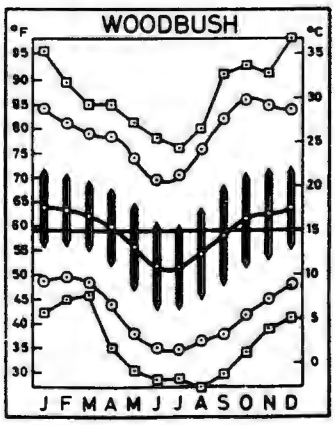
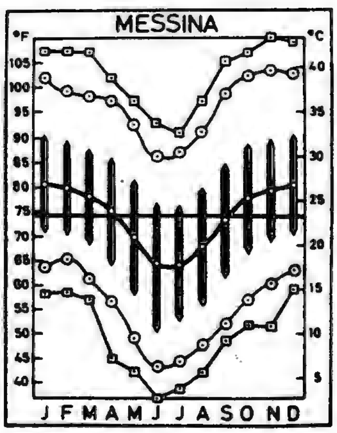
°C
J F M A M J J A S O N D


WOODBUSH
°F
°C
J F M A M J J A S O N D


MESSINA
°F
°C
J F M A M J J A S O N D

Appendix F: Pump and power equipment used at the Mzimhlophe Secondary School in KwaNdebele

An ELEPON submersible sewage pump, with the following specifications:

- required electrical power source: 220 volt AC
- mechanical power output: 250 watt
- current drawn when running: 2.8 ampere
- electrical power drawn when starting up (estimated): 4-5 kilowatt

An inverter purchased from National Luna, with the following specifications:

- 24 volt DC to 220 volt AC
- nominal 1 kilowatt power output (designed to run single-phase induction motors with a maximum mechanical power output of 560 watt)
- efficiency of 60-75 %, depending on adjustment to specific load
- built-in regulation of battery charge current
- built-in protection against excessive battery discharge

Two BP 252 photo-voltaic panels (each rated at 52 watt-peak).

Two SABAT batteries (100 amp-hour each).

Appendix G: Areas in the former homelands with potential for the implementation of biogas technology

Table G.1: Districts in the former homelands with the most favourable cattle/people ratios and climatic conditions.

DISTRICT	CATTLE/PEOPLE RATIO	CLIMATE
BOPHUTHATSWANA		
Ganyesa	0.9	good in part
Kudumane	0.9	good in part
Lehurutshe	0.5	good
Madikwe	0.5	good
Mankwe	0.5	good
Molopo	0.4	good
GAZANKULU		
Mhala	0.4	good
KANGWANE		
Kamhlushwa	0.4	very good
KWAZULU		
Enseleni	0.5	very good
Hlabisa	0.7	very good
Hlanganani	0.4	good
Ingwavuma	1.0	very good
Inkanyesi	0.5	very good
Mahlabatini	0.8	very good
Msinga	0.6	very good
Nkandla	0.7	very good
Nongoma	1.0	very good
Nqutu	0.7	good
Okhahlamba	0.5	good
Simdlangentsha	0.5	very good
Ubombo	1.0	very good

DISTRICT	CATTLE/PERSON RATIO	CLIMATE
TRANSKEI		
Bizana	0.7	very good
Centane	0.6	very good
Cofimvaba	0.5	good
Engcobo	0.5	good
Gatyana	0.6	very good
Gcuwa	0.4	very good
Kwabhaca	0.5	good
Libode	0.5	good
Lusikisiki	0.6	very good
Maxesibeni	0.5	good
Mqanduli	0.4	very good
Mt Fletcher	0.7	good in part
Ngqeleni	0.6	very good
Nqamakwe	0.4	good
Qumbu	0.6	good
Siphaqeni	0.7	very good
Tabankulu	0.6	good
Tsolo	0.6	good
Umzimkulu	0.8	good
Umzimvubu	0.5	very good
Xalanga	0.7	good
Xhora	0.7	very good

Sources: Calitz and Grove (1991); and Personal communication with N G Meyer, Development Bank of Southern Africa.

Appendix H: Installation costs of biogas plants

Table H.1: Basic installation costs of the floating-drum plant comprising a cylindrical ferrocement digester and a mild steel gas drum (digester volume 10 m^3).

	Labour costs (1992 rand)	Material costs (1992 rand)	Total costs (1992 rand)
Gas drum	350	750	1100
Digester; mixing & collection boxes	900	1400	2300
Gas piping	90	300	390
Subtotal	1340	2450	3790
Digging hole; filling digester	465		465
Total	1805	2450	4255

Table H.2: Basic installation costs of the floating-drum plant comprising a tapered brick digester and an HDPE gas drum (digester volume 8 m^3).

	Labour costs (1992 rand)	Material costs (1992 rand)	Total costs (1992 rand)
Gas drum	80	980	1060
Digester; mixing & collection boxes	600	1530	2130
Gas piping	90	300	390
Subtotal	770	2810	3580
Digging hole; filling digester	390		390
Total	1160	2810	3970

Table H.3: Basic installation costs of the flexible cover plant comprising a ferrocement digester and a PVC Elvaloy gas holder (digester volume 10 m³).

	Labour costs (1992 rand)	Material costs (1992 rand)	Total costs (1992 rand)
Gas holder	15	650	665
Digester; mixing & collection boxes	520	1420	1940
Gas piping	90	300	390
Subtotal	625	2370	2995
Digging hole; filling digester	390		390
Total	1015	2370	3385

Table H.4: Basic installation costs of the ferrocement fixed-dome plant (digester volume 9 m³).

	Labour costs (1992 rand)	Material costs (1992 rand)	Total costs (1992 rand)
Digester; mixing box; compensation tank	1390	2000	3390
Gas piping	90	300	390
Subtotal	1480	2300	3780
Digging hole; filling digester	540		540
Total	2020	2300	4320